THE CORAL REEF PROBLEM

WILLIAM MORRIS DAVIS

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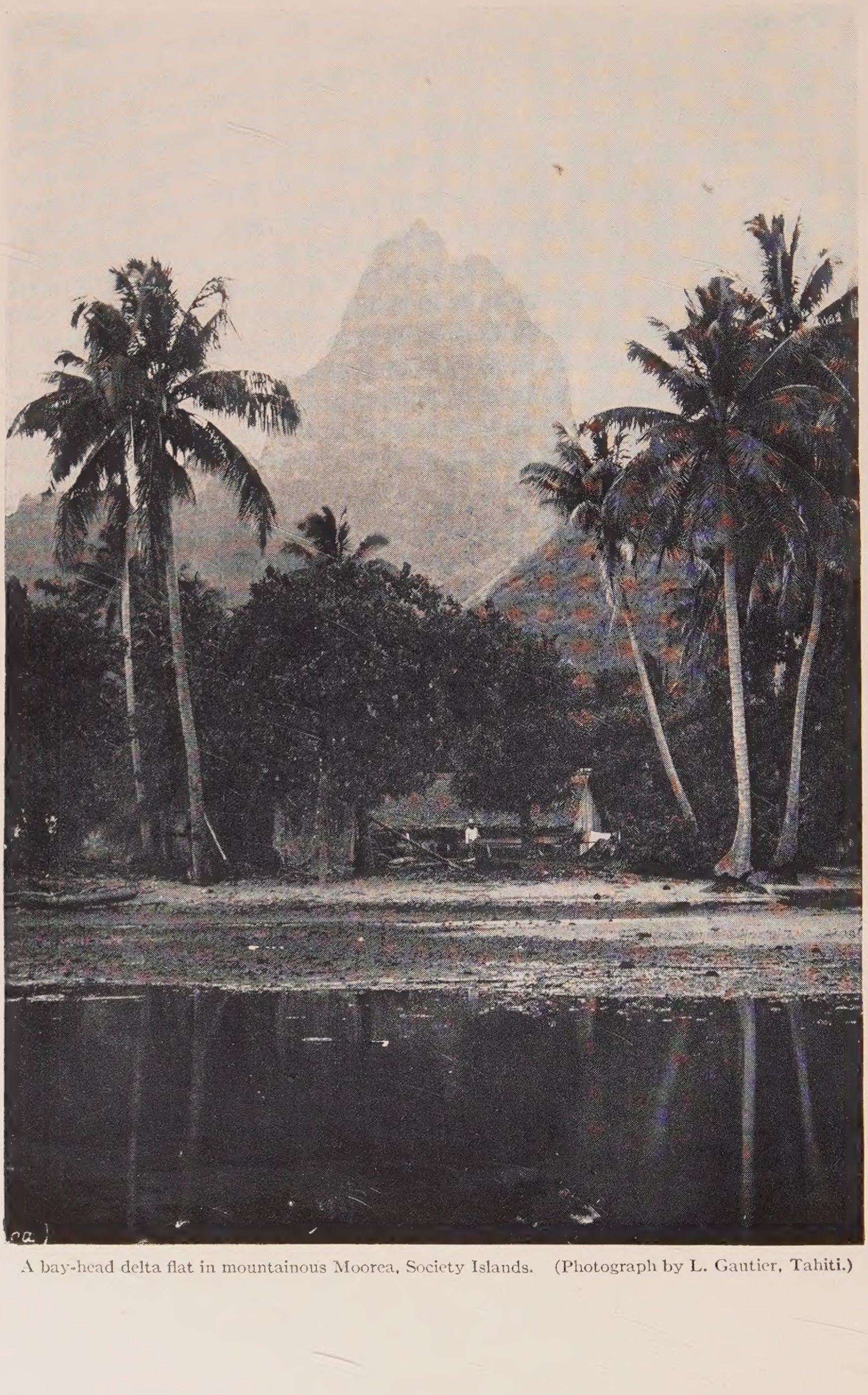

A bay-head delta flat in mountainous Moorea, Society Islands. (Photograph by L. Gautier, Tahiti.)

To the Memory of

NATHANIEL SOUTHGATE SHALER

Who, as My Teacher at Harvard Sixty Years Ago,
First Led Me to Know in Outline Darwin's Theory of Coral Reefs,
and Who, Ten Years Later,
Inviting Me to Return to Harvard as His Assistant in Field Geology,
Opened the Door of Opportunity through which
My Life Work was Entered Upon,

This Book on the Coral Reef Problem,

the Delayed Product of a Voyage Across the Pacific in 1914,
Subventioned by the Shaler Memorial Fund of Harvard University,

is Gratefully Dedicated

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PART I

LEADING THEORIES OF CORAL REEFS

INTRODUCTION

Through the middle of the nineteenth century the coral reef problem had a glamour about it, in part because of the romantic remoteness of reef islands and the primitive customs of their inhabitants in the distant Pacific, in part because of the ingenious simplicity of Darwin's theory by which reefs of different kinds were so satisfactorily shown to be evolved from a simple initial form. But before the century closed, the reefs and their inhabitants became more familiarly known; and Darwin's theory, after having been universally accepted for a generation, came to be disputed. The coral reef problem then took its place in a matter-of-fact way as one of many for which a final solution had yet to be established.

Coral reefs should nevertheless be still regarded, especially in their barrier and atoll forms, as among the most extraordinary of natural structures. The observant traveler must marvel, however often he has seen them, at the steep ascent by which they rise from great depths to the ocean surface; and he must admire the firm resistance with which, in spite of the minuteness of their builders, they withstand the unceasing and at times furious onslaught of the trade wind surf. In my own case when, rather late in life, I undertook the serious investigation of their long debated origin, a certain measure of embarrassment was felt on discovering that the most careful analysis I could make of it compelled me to dissent from the views reached by many of my predecessors, with some of whom I had been more or less associated; but this embarrassment was relieved when it appeared that the dissent led me back to Darwin's original theory of upgrowing reefs on subsiding foundations, as announced nearly a century ago; for of all coral reef theories, Darwin's seems to me the best argued, in spite of his youth when he published it. Although his argument was not complete, the chief factors that he failed to perceive give unqualified support to his theory when they are recognized; and two additional factors—the changes of sea level and of sea temperature in the Glacial period, of which he can have had no knowledge whatever—far from invalidating his views, merely supplement and enlarge them.

My entrance into the coral reef problem was occasioned by learning that what I have called "Dana's confirmation of Darwin's theory" (1913)—namely, the indication of subsidence given by the embayments in the central volcanic islands of barrier reefs—had been overlooked by nearly all students of the problem for more than fifty years since Dana's

announcement of it. The interest in the problem thus aroused led me to spend the greater part of 1914 on the Pacific, thanks to the aid of a liberal grant from the Shaler Memorial Fund of Harvard University, supplemented by an invitation which carried with it a generous subsidy from the British Association for the Advancement of Science to attend its meeting of that year in Australia. I then visited thirty-five reef-encircled islands as well as a long stretch of the Queensland coast back of the Great Barrier Reef; the itinerary of this voyage is given in detail in Chapter VII.

It was my intention on returning home at once to prepare a narrative of the voyage and a statement of the conclusions I had been led to adopt; but, on continuing the review of the problem which I had previously begun (1914), it seemed advisable to enlarge the scope of my work so that it should attempt to cover the whole subject. Hence only a condensed summary of the results gained on the Pacific was published in 1915, and the present volume was postponed. Progress in the enlarged discussion was slow because of its many complications, and my work upon it was much interrupted by the distractions of the World War. The delay thus occasioned was, however, by no means disadvantageous, for it gave me time to gather and to reflect upon an increasing store of pertinent information from many books and articles and charts. It also enabled me gradually to reach an understanding of various matters which had before been obscure or unnoted. Among these are: the conditions under which young volcanic islands remain reef-free and exposed to the attack of the surf, and the change from those conditions which later permits the islands to become reef-encircled; the testimony furnished by the visible forms of certain volcanic islands as to the great subsidence that they have suffered; the compelling evidence for subsidence given by the disappearance of large volumes of detritus from maturely dissected, reef-encircled islands; and, following a principle embodied in Daly's Glacial-control theory although departing widely from the postulates on which that theory is based and from the conclusions to which it leads, the ocurrence of marginal belts around the coral seas, where reef growth appears to have been interrupted during the Glacial period. These and various other aspects of the problem have been set forth in a preliminary way in a number of articles published during the last twelve years and listed in the Bibliography at the end of this book: the results thus gained are here all brought together.

Shortly after the occurrence of the marginal belts of the coral seas was recognized opportunity came in 1923 to visit the Lesser Antilles, where the peculiar features expectable on marginal-belt islands were found to be developed in the most striking manner. For there the reefs, mere timid Postglacial novices standing well back from the outer margin of their banks, were found to be strongly unlike the stalwart veterans of the true coral seas in the Pacific.

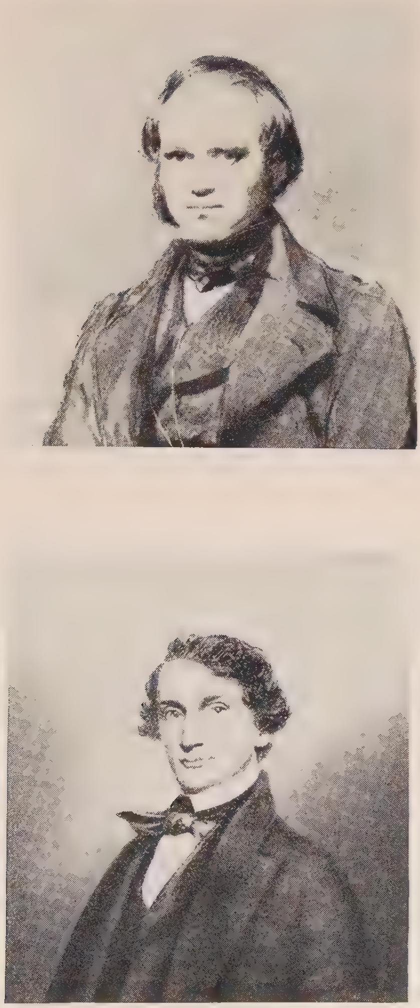


FIG. 1—Portraits of Charles Darwin (top) and James D. Dana (bottom) in their youth, about the time when they were most actively engaged upon the coral reef problem. (Photographs from the Gardner Collection, Harvard University.)

It should here be emphasized that independent evidence as to the value of competing theories of reef origin can be best obtained not from the reefs themselves, but chiefly from the physiographic features of the coasts, either insular or continental, that are bordered by fringing reefs or fronted by barrier reefs; and also from the structure of elevated reefs. It is for this reason that the following pages are so largely occupied with the physiography of land forms rather than with the biology of coral reefs. The biology and especially the symbiosis of the reefs are unquestionably important subjects in themselves, but the opportunity for the establishment and growth of reefs is so largely determined by the physiographic conditions of insular and continental coasts, over which reef-building organisms have no control, that those physiographic conditions necessarily assume the leading rôle in the problem under discussion.

Plan of the Present Volume

The object of the present volume is to examine the various theories that have been proposed to account for coral reefs, in order to discover which one of them or which combination of several of them is most successful in doing so. After a general account of the various kinds of reefs and of the processes, organic and inorganic, in operation upon them, the leading theories of coral reef origin will be set forth: particular attention will be given to conditions postulated and to consequences following therefrom; for it is only when all the postulates and all the consequences of all the theories are understood that one is able to make a critical and impartial test of the success of any theory in meeting all the facts. Hence, it will not be until after the theories are reviewed that a large body of facts will be presented, beginning with certain islands of the cooler seas, never reef-defended, for they also enter the problem; then proceeding to the islands of the marginal belts of the coral seas, alternately reef-defended in non-Glacial epochs and reef-free in Glacial epochs; and finally taking up the continental coasts, the islands, and the persistent reefs of the coral seas. The islands of the latter region will be subdivided according to their stage of dissection, according to the kind of reefs associated with them, and according to the changes of attitude that they have suffered either by subsidence or upheaval. Atolls will be treated in a final chapter, more in view of what has been learned about other reefs than of what atolls themselves disclose as to their origin, because they disclose so little.

The main conclusion of my many pages is that Darwin's theory of upgrowing reefs on intermittently subsiding foundations, extended by introducing the effects of Glacial changes of sea level and temperature, as proposed by Daly, and by adding such minor modifications as may be called for in special cases, will deservedly regain in the present century the general acceptance which it enjoyed through the middle of the past century.

Hints to Readers

Text references to authors are made in parentheses by date and page. When several books or articles by the same author have been published in a single year, they are distinguished, after the first, by the letters *a*, *b*, *c* following the date. All articles cited are given in the Bibliography at the end of the book. Charts published by the Hydrographic Office or by the Coast and Geodetic Survey of the United States are indicated by the letters HO or CS and their catalog number; British Admiralty charts are indicated by BA. Distances are given in nautical miles, heights in feet, and depths in fathoms, unless otherwise stated. In so far as illustrations are reproduced from my pencil sketches it should be understood that, while they are fairly faithful in outline, they are very deficient in representing vegetation. Many items, taken from charts or from the "Pilot" handbooks of the various oceans, are introduced without citation of their source.

FIG. 2

FIG. 3

FIGS. 2, 3—Views of a fringing reef, looking on and off shore at Port Boise, southeastern end of New Caledonia. New Caledonia pines are shown in profile of the upper view; the cliffed headland of Cape Ndua is seen in distance of lower view.

CHAPTER I

OBSERVABLE FEATURES OF CORAL REEFS

Fringing Reefs, Barrier Reefs, and Atoll Reefs

Coral reefs are limited to the warmer seas, where corals and the associated organisms which contribute most largely to reef building flourish down to depths of 20 or 25 fathoms. The three typical forms of fringing, barrier, and atoll reefs grade into each other so well that they are usually regarded as stages of an evolutionary sequence; but the sequence thus constituted is not theoretically complete, as will appear in the sequel. All forms of reefs are composed of limestone or of its magnesian relative, dolomite, and are the product of various lime-secreting organisms, chiefly corals. The young or larvae of the coral polyps, of pin-head size, are produced in vast numbers on living reefs and are then passively drifted far and wide by ocean currents. If they are cast upon gravel or sand beaches, they cannot survive because the beach material is shifted about by the beach-building surf. But such of them as may chance to reach a reefless shore of firm rock in water of proper temperature—for example, the margin of a recent lava flow on a volcanic island in a torrid ocean—may attach themselves there and grow, at first in small patches, later in larger communities; and when they are reënforced by the similarly chance arrival of various associated organisms, especially by the calcareous algae known as nullipores, the rock surface will become completely covered with the calcareous framework of the reef builders; thus a fringing reef in its primitive stage is established. The reef may thereafter increase in size by outward growth. But reef-building corals and their associates may also establish themselves upon dead shells that lie quietly on a submarine shoal, or upon pebbles and cobbles such as may be swept out by a flooded river and left on a muddy delta front at a depth where they are not shifted by the waves, yet not below the limit of coral growth. It is conceivable that, if such points of support are numerous enough, an atoll or a barrier reef might be built up from them.

Fringing Reefs

Fringing reefs (Figs. 2 and 3) are closely attached to an insular or continental shore; but it should be noted at once that certain reefs rising from the shallow sea floor adjoining the island of Mauritius in the Indian Ocean were described by Darwin in his chapter on fringing reefs as though he regarded them as belonging in that class, in spite of their standing two or three miles from the island shore. When a reef of the fringing kind fronts the open ocean it repeats the features of barrier reefs so closely that, except for the absence of a lagoon, its description may be taken from

theirs, as given below. In the case of the many fringing reefs that are found along the inner side of a barrier-reef lagoon, the shore line of the land back of the fringe is always embayed, as if by submergence; and the reef is weak or wanting in the embayments where streams mouth and deltas are formed, because corals do not grow in fresh or turbid water. The inter-bay spurs of the coastal slope usually descend with moderate declivity below sea level; but they are sometimes cut back by the lagoon waves in low bluffs, as in Figure 4, from 5 to 50 feet in height, in front of which lies

FIG. 4—Diagram of spur-end fringing reefs and bay-head deltas; the spur ends are a little cut back at mean tide level.

an abraded platform of firm rock several times wider than the bluff height, more or less strewn with cobbles and gravel. Then comes the fringing reef flat which wraps around the submerged spur slope. The reef flat, from a few feet to a quarter mile in width, submerged at high tide, consists for the most part of dead reef rock. Growing corals and other organisms are found chiefly on the submerged exterior slope of the reef: there the fringe tends to widen by outward growth. At time of storms, fragments and blocks of coral up to five or ten feet in diameter are torn from the reef face by the lagoon waves; some of the fragments are thrown on the reef flat where they slowly disintegrate; others are shifted down the reef face where they accumulate in a talus at a depth of a few fathoms in the usually quiet lagoon water. Hence corals do not grow to so great a depth here as on the more exposed face of an open fringing reef or barrier reef, where the wave action is much stronger and where the reef detritus is therefore swept farther down the outer reef slope.

The bay-head deltas between spur-end fringing reefs are formed of detritus washed down from the valleys inland. They are usually shaded by groves of the coconut palm, "that giraffe of vegetables, so graceful, so

ungainly," as Stevenson aptly put it; and here are the sites of native villages. The beached fronts of the deltas are free from coral reefs.

Barrier Reefs

Barrier reefs, with reef flats measuring from 20 or 50 to 1000 feet or more in width, are separated from the adjacent coast by a lagoon commonly from 20 to 40 fathoms in depth and from half a mile to ten or more miles in breadth. A typical example is shown in Figure 6. In some close-set

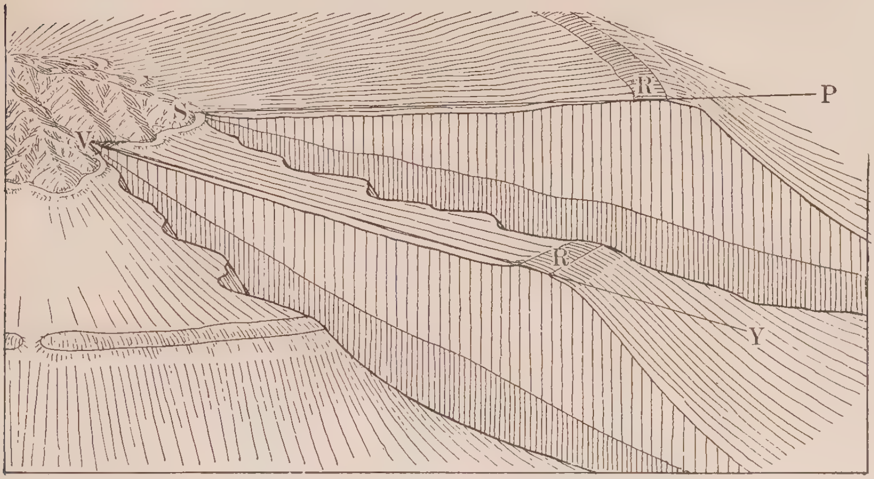


FIG. 5—Block diagram of a barrier reef, showing its inferred submarine structure.

barriers the lagoon is so narrow that the reef might be described as an offset fringe. Indeed, some barrier-reef lagoons gradually decrease in breadth in one direction or the other until a typical barrier reef is transformed into an equally typical fringing reef. This is the case with the ovoid Rossel reef in the Louisiade Archipelago east of New Guinea; the barrier reef, which extends eight miles to the east and farther to the west in long loops, becomes a fringe along the north and south sides of the island. On the other hand, the lagoons of certain other barrier reefs are so little occupied by islands that their reefs almost become atolls. Reefs of this kind will be called almost-atolls.

A block diagram (Fig. 5) shows, with little exaggeration of vertical over horizontal scale, a part of a volcanic island encircled by a barrier reef and thus exhibits the great terrace-like mass of which the reef is the crowning rim. The foundation of the terrace mass is here given a submarine profile which continues in a reasonable manner the visible slope of the central island under the sea-level lines, *SP*, *VY*. As thus interpreted, the submarine part of the island descends with increasing depth below the terrace-making limestones of the lagoon floor and the rimming reef, for which it serves as a foundation. An alternative foundation profile is

sometimes conceived as a broad and nearly level platform, but little below the limestones of the lagoon floor and reef, as if the platform had been produced by abrasion of the island. But this interpretation is usually

FIG. 6—The island of Matuku, Fiji, and its barrier reef; from the "Challenger" Narrative.

inadmissible, because in such case the waves that abraded the platform must have cut back the island in strong cliffs, and such cliffs are prevailingly absent. Certain exceptional islands in which shore cliffs occur back of barrier-reef lagoons will be described in later chapters.

Just as a fringing reef is a small terrace-like structure built up from a

sloping foundation, so the broader and presumably thicker mass rimmed by a barrier reef is a large terrace-like structure similarly placed. The term "coral reef" has sometimes been employed to name the entire terrace-like structure thus inferred to exist and not merely the relatively small superstructure which rises from the lagoon-floor level of the terrace to the sea surface. Naturally, this enlarged meaning of the term is objected to by those who do not regard the whole sub-lagoon mass of the terrace as of organic origin; but in my own opinion the larger inter-

FIG. 7—A double barrier reef; north coast of Vanua Levu, Fiji; HO 2856.

pretation of the submarine terrace here given is, as a rule, more reasonable than any other.

Barrier reefs usually follow in a general manner the coast which they adjoin and which is always embayed, as in Figures 6 and 8; but they sometimes turn outward in irregular courses, as if to loop around vanished islets. They are nearly always linear, but they are sometimes double, as in Figure 7, and they are occasionally subdivided into complex forms. For example, the great barrier reef of Tagula, in the Louisiade Archipelago, measuring 112 by 30 miles, is broad and continuous in the southeastern or windward part of its oval circuit, but its northwestern part is resolved into many small atoll-like rings or loops, as in Figure 188. A number of the Maldive atolls, west of India, are resolved into little loops all around their circuits.

In general a barrier-reef flat, like that of a fringing reef, is not occupied

by living forms. Growing organisms occur mostly on the shallow exterior slope of the reef. It seems to be chiefly on reef flats where the tidal range is rather strong, as on the Great Barrier Reef of the northeast, or Queensland, coast of Australia, 1000 miles in length, that the flat is largely overgrown with living corals, emerged at low water, and well shown in the plates of Kent's great work on that reef (1893). The distribution of organisms on Murray Island, a northern member of this great reef, has

FIG. 8—The eastern end of Kandavu, Fiji, showing the relation of reef passes to embayed valleys; HO 2858.

been statistically studied by Mayor (1918). Barrier-reef flats ordinarily have a monotonous and often muddy surface on which are strewn reef blocks of all sizes up to five or ten feet or more, in various stages of disintegration. The blocks are usually blackened by a thin coating, apparently of algous growth, and they have therefore been repeatedly mistaken for volcanic rocks, which are common on delta flats; but a blow with a hammer shows the reef blocks to consist of glistening white limestone. A process of cementation, involving the solution and redeposition of calcite, must be at work below the surface of the reef flat, for the great volume of the reef consists of solid rock, in which well preserved corals and shells are by no means always conspicuous. Furthermore, a chemical alteration from limestone to dolomite appears, according to Skeats (1903, p. 125; 1918a), to take place within the reef rock at moderate depths.

The shallower part of the outer profile of a reef is sometimes precipitous, sometimes gently sloping. Here reef-building corals and other lime-secreting organisms, especially the nullipores above mentioned, abound to depths of 15 or 20 fathoms. Their forms are more massive than those in the lagoon, but they are not easily observed by reason of the almost unceasing activity of the surf. Farther outward the profile is continued in a slope of gentle declivity, chiefly composed of reef detritus, to a depth of about 40 fathoms at a distance of 600 or 800 feet from the reef shore line. There the gentle slope changes rather rapidly to a steep pitch, sometimes inclined at an angle of 40° or 45°. The terms "slope" and "pitch" will be frequently used in the sense here defined.

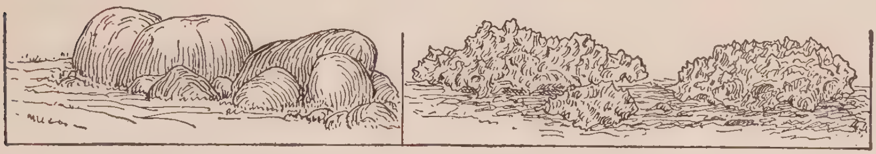


FIG. 9—Torrent-borne, rounded, volcanic boulders on delta plains and ragged blocks of disintegrating coral limestones on reef flats.

The roaring breakers that fall almost unceasingly on the outer face of the reef and surge over the flat are in striking contrast to the more placid lagoon waters with their thickets of branching corals. Jukes wrote vividly of the heavy surf on Raines Island, part of the Great Barrier Reef of Australia, eighty years ago: "The long ocean swell [coming in from "almost unfathomable depth right up to the outer slope or submarine wall of the reef"] being suddenly impeded by this barrier, lifted itself in one great continuous ridge of deep blue water, which, curling over, fell on the edge of the reef in an unbroken cataract of dazzling white foam. Each line of breakei was often one or two miles in length, with not a perceptible gap in its continuity . . . The unbroken roar of the surf, with its regular pulsation of thunder . . . was almost deafening, yet so deep-toned as not to interfere with the slightest nearer or sharper sound" (1847, Vol 1, pp. 121, 122).

The organisms on the growing face of a well established reef—that is, on the shallower outer slope of the reef to depths of 15 or 20 fathoms—tend to add to its volume by upward and outward accretion. Tidal and other currents bring oxygen and food to them; and, as the currents are largely wind-driven, it is on the windward side of a reef circuit that the reef-building organisms grow most abundantly and rapidly. The heavy surf restricts organic growth by its violence, especially at time of storms; the more salient forms are then broken from their base. But the surf is also helpful to the growth of the firmly rooted forms by keeping them free from fine detritus, which is either drifted out to the deeper part of the slope or swept over the reef into the lagoon.

Attention has been called in recent years by Gardiner (1898), Howe (1912), Glock (1923), Setchell (1915, 1924) and others, to the important part played by nullipores as coral binders on the reef face. This matter had long ago been noted by Darwin: he recorded that on Keeling Atoll, in the eastern Indian Ocean, nullipores commonly make "a continuous smooth convex mound" along the reef shore, like an artificial breakwater; and he added that "other coral reefs are protected by a similar thick growth of Nulliporae on the outer margin, the part most exposed to the breakers, and this must effectually aid in preserving it from being worn down" (1842, p. 10; also pp. 25, 42). This feature of reef growth is especially mentioned in Setchell's account of Rose Atoll in the Samoan group, quoted in the final chapter of this volume.

Reef Detritus

The growth and the wear of reef-face organisms provides a continuous supply of detritus, some of which is shifted down the outer slope of the reef as far as waves and currents have power to move it; and this seems to be at a depth of 40 or 45 fathoms, where the gentle slope changes to the steep pitch. Here it is to be supposed that the detritus descends like a talus, with gradually decreasing declivity, into the quiet water of great depths, where it may reach the nearly level sea bottom on which the reef foundation as well as the reef talus is supported. Gardiner has given a number of true-scale profiles of these slopes (1915). The coherence of the growing organisms on the reef face, the strength of waves and currents, especially at time of storms, and the amount and texture of the detritus that they remove from the growing face appear to be the chief factors in determining the angle of the gently descending exterior reef slope. As these factors remain fairly uniform on a well established reef, so long as the relative level of reef flat and sea surface is not disturbed, the slope may be regarded as one of adjustment with respect to the waves and currents at the present ocean level. The slope is therefore an insular shelf, like a continental shelf in miniature; for continental shelves also appear to have their outer margin at a depth of about 40 fathoms: according to Daly "the charts of the world show the break of slope on the shelves to be near the 40-fathom line" (1915, p. 199).

Darwin appears to have recognized the processes at work on the exterior profile of coral reefs, for he generalized as follows: "As the external slope of the reef is the same round the whole of this [Keeling] atoll and round many other atolls, the angle of inclination must result from an adaptation between the growing powers of the coral, and the force of the breakers, and their action on loose sediment. The reef, therefore, could not increase outwards, without a nearly equal addition to every part of the slope, so that the original inclination might be preserved, and this would require a large amount of sediment, all derived from the wear of corals and shells, to be added to the lower part" (1842, p. 74).

A barrier-reef flat is sometimes surmounted by low islets or islands of reef sand, without or with vegetation. Such islets are most often found at the ends of reef segments adjoining a pass, evidently because the long-shore drift of the sand on the reef-front beaches is there halted, from whichever way it comes, by the waves that are refracted as they sweep into the pass, so that they beat upon both of its transverse shore lines. Reef islands are modified by storm waves: where they are worn away on a retrograding beach, their firmly cemented underlayers may be exposed as ledges of resistant limestone.

An important but undetermined share of reef-face detritus is swept, especially at high tide and in stormy weather, upon the reef flat and across it into the lagoon, provided that sand islands do not stand in the way: in that case the detritus may be swept up to the island beaches and there comminuted until it is fine enough to be swept elsewhere. On narrow and low reefs every breaker causes a heavy surge to sweep over into the lagoon; on broader reefs the traversing surges are less powerful, but when aided by flood tide and an onshore gale they constitute an effective transporting agency. At such times the larger reef blocks are shifted and all the finer detritus on the flat is adrift lagoonwards; thus the flat is broadened and the lagoon is shoaled.

A barrier reef is commonly interrupted by passages, or "passes," which often become broadly open breaches on the leeward curve of the reef circuit. In close-set barriers the passes frequently stand opposite to the embayed valleys of the central island, as in Figure 8, where the fringing reefs also are interrupted; and this suggests that the interruptions in the original fringing reef have been perpetuated in the passages of the barrier reef that has been developed from the fringe. But it often happens, especially on the windward curve of well offset barriers, that the passes are much fewer in number than the embayed valleys in the corresponding part of the island's shore. The passes there may indeed be wanting for miles together, as if they had been filled during the later growth of the barrier.

Of all prospects afforded by the coral seas, the most beautiful are those in which one reef-encircled island is viewed across a belt of intervening sea from the slope of a not-distant neighbor. Concerning such a view of Moorea, or Eimeo, in the Society group, as seen from the slopes of Tahiti, Darwin wrote while on the voyage of the *Beagle:* "The island . . . is completely surrounded by a reef. At this distance a narrow but well-defined line of brilliant white was alone visible, where the waves first encountered the wall of coral. The glassy water of the lagoon was included within this line, and out of it the mountains rose abruptly. The effect was very pleasing, and might aptly be compared to a framed engraving, where the frame represented the breakers, the marginal paper the lagoon, and the drawing the island itself. . . . On the lofty and broken pinnacles, white massive clouds were piled up, which formed an

island in the blue sky, as Eimeo did in the blue ocean" (1840, pp. 484, 485). The clouds were there again when I enjoyed the same glorious view in September, 1914.

Atoll Reefs

If the central island of a barrier reef be withdrawn and the lagoon be imagined to occupy all the space enclosed by the reef, the description above given for a barrier reef will apply to that of an atoll. Atolls are inscrutable structures: the nature of their reef foundation is highly problematical, instead of being surely determined as in fringing reefs and fairly inferred as in barrier reefs. The origin of sea-level atoll reefs and their enclosed lagoon floors is therefore the center of the coral reef problem. In the absence of numerous and deep borings on atolls, the problem can be best solved by the study either of elevated atolls or of sea-level barrier reefs and their enclosed islands. It is for this reason that sea-level atolls are given relatively little attention in this volume.

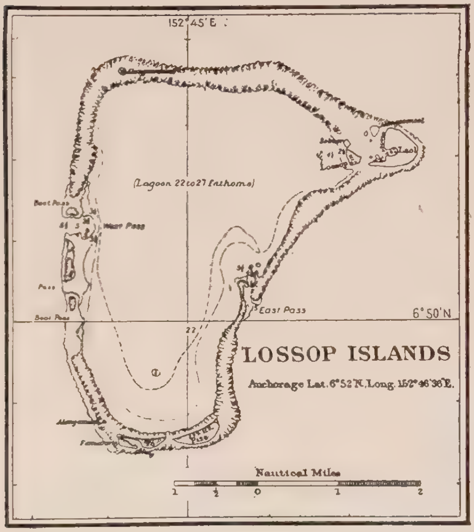


FIG. 10—Lossop Atoll, Caroline Islands: HO 1752.

Darwin wrote of Keeling Atoll in the eastern Indian Ocean, the only atoll upon which he landed in the course of his voyage around the world: "There is to my mind a considerable degree of grandeur in the view of the outer shore of these lagoon islands [atolls]. There is a simplicity in the barrier-like beach, the margin of green bushes and tall cocoa-nuts, the solid flat of coral rock, strewed here and there with great fragments, and the line of furious breakers, all rounding away towards either hand. The ocean, throwing its waters over the broad reef, appears an invincible, all-powerful enemy, and yet we see it resisted and even conquered by means which at first seem most weak and inefficient. . . . It is impossible to behold these waves without feeling a conviction that an island though built of the hardest rock . . . would ultimately yield and be demolished by such irresistible forces. Yet these low, insignificant coral islets stand and are victorious; for here another power, as antagonist to the former, takes part in the contest. . . . Let the hurricane tear up its thousand huge fragments; yet what will this tell against the accumulated labour of myriads of architects at work night and day, month after

month" (1840, p. 547). Darwin therefore viewed an atoll as "not a wonder, which at first strikes the eye of the body, but rather, after reflection, the eye of reason" (1840, p. 553).

The low sand islands of atolls are often inhabited, but they offer no safe abode. Cooper wrote: "In May, 1877, when I was sailing in a cutter in the Fiji Group, there was a terrible wave which swept away thousands of the inhabitants of the atoll islands, some of which disappeared altogether"

FIG. 11—View of an atoll. (Redrawn from Dana: Geology, U. S. Exploring Expedition, 1849, p. 33.)

(1880, Vol. 1, p. 28). This wave is believed to have come across the Pacific from the earthquake of Iquique, Peru.

The Lagoons of Barrier and Atoll Reefs

The lagoons of clear blue water enclosed by barrier or atoll reefs are ordinarily from 10 to 30, occasionally from 40 to 50 fathoms deep. The lagoon floor is smooth or gently undulating. Its greatest area is commonly strewn over with fine detritus, supplied in part by outwash from the central island, if one is present, but more largely by inwash from the reef, by the calcareous frames of small organisms that float in the lagoon waters during their life, or by organisms growing on the lagoon floor itself. The floor may be varied by patches of growing corals in its shallower parts or by tower-like masses of corals rising from its deeper parts; also by more extensive reef patches or by "lagoon atolls," that is, small annular reefs enclosing little lagoons in the larger lagoon. In the protected lagoon waters the larger corals sometimes grow up, especially near the reef passes, with delicate branches or curved fronds of marvelous beauty. It is these submarine coral gardens that excite the admiration of all observers; and it would indeed be difficult to give a worthy description of them, so marvelously varied are their forms and so delicately modulated are their colors as seen through the crystal-clear water. Wallace wrote nearly sixty years ago of the fringing reef at Amboyna in the Dutch East Indies: "For once, the reality exceeded the most glowing accounts I had ever read of the wonders of a coral sea. . . . The clearness of the water afforded me one of the most astonishing and beautiful sights I have ever beheld. The bottom was absolutely hidden by a continuous series of corals, sponges, actiniae, and other marine productions, of magnificent dimensions, varied forms, and brilliant colors" (1869, p. 301).

As a barrier or atoll reef is approached from within its lagoon, it is sometimes discovered to rise with almost wall-like steepness from blue water; but the lagoon floor more frequently ascends to the reef in a sloping shoal of white reef sand, swept over from the reef face by the un-

ceasing surges of the trade-wind surf. It is over these sloping sand shoals that the lagoon water assumes the indescribable greenish-blue color that is associated with coral reefs. The sand shoals back of narrow reefs are sometimes dotted with reef blocks from three to five feet in diameter, evidently drifted over the reef by storm waves: the blocks are usually overgrown with living corals, while the adjoining sands are barren.

Lagoon Deposits

It may be inferred that the effect of inwashed detritus in shoaling a lagoon floor will be greater in small lagoons than in large ones, because in small lagoons the detritus supplied from a given length of reef front will aggrade a smaller floor area than in large lagoons. Daly has shown the correctness of this inference by a statistical study, in which atoll lagoons having widths up to 5, 10, 20, 30, and 60 kilometers are found to have average depths of 16, 28, 41, 51, and 68 meters (1915). Conversely, the aggradation of large lagoons must be more largely determined by locally supplied than by inwashed detritus. Vaughan has shown this to be the case for the wide lagoon of the Florida reefs, where he estimated the lagoon-formed oölites to be about 100 times greater in volume than the coral-formed rock; on Andros Island in the Bahamas the ratio was taken to be about 1000 to one (1914). Inasmuch as locally supplied detritus will increase as the lagoon area increases, a large lagoon may be as rapidly aggraded by this means as a small one.

The lagoon of a fully developed barrier reef is so well enclosed, and its waters are usually so quiet as compared with the rolling sea outside, that its activities may be underrated. There is ordinarily an alternation of flood and ebb tidal currents at the passes; and here is an abundant outflow of sea water from the surges that cross the reef flat, especially at high tide and all the more during gales. The excavation of lagoon floors by the solvent action of the sea water that flows over them has been emphasized by some observers, but this process is now generally discredited; for the occurrence of fine calcareous sediments over the floor of most lagoons indicates that, whatever measure of dissolved matter is carried away, a much larger measure of sediment remains.

Although the lagoon waters are ordinarily placid and clear, they become turbid when agitated by strong winds; the finer sediments must then be distributed and smoothed. Darwin clearly recognized the working of this process when he wrote of the lagoon floor: "The greater part in most lagoons is formed of sediment; large spaces have exactly the same depth, or the depth varies so insensibly, that it is evident that no other means, excepting aqueous deposition, could have leveled the surface so equally" (1842, p. 26). At times of storm the turbid lagoon waters drift through the leeward reef passes into the adjacent sea. Darwin quoted Moresby as reporting that "during the change of the monsoon, the sea is discoloured to a distance off the entrance into the Maldiva and Chagos atolls" (1842,

p. 29). Gardiner, also writing of the Maldives, said: "It is only in a few protected situations, where the depth is as great as 40 fathoms or more, that the lagoon bottom appears not to be churned up by the currents and waves. In heavy weather the lagoon water is almost milky, and floating surface nets are almost useless on account of the enormous amount of mud in suspension. The total amount of mud that passes out of the lagoon in the water is enormous" (1903, p. 210). It would therefore seem that the shoaling of lagoons is retarded by the exportation of fine sediments.

In my own experience on the Pacific I saw the water of barrier-reef lagoons made turbid by strong waves under high winds on two occasions. The first was in eastern Fiji during a moderate hurricane, when the lagoon around the island of Vanua Mbalavu became milky gray; and no wonder, for the lagoon waters were whipped into a state of violent agitation that I had not expected in view of their reputation for placidity. The second was in the broad lagoon of the Great Barrier Reef of Australia, during a gale which raised waves high enough to make a good-sized steamer roll uncomfortably; here the water was only moderately clouded, but it was distinctly different from the clear blue that prevails in fine weather. Yet, in spite of the large amount of fine sediment that may thus be carried out of a lagoon, its floor is seldom clean swept to firm rock but is in practically all cases covered with loose sediments if not with growing organisms.

Of the latter, an excellent account is given by Judd regarding the lagoon of Funafuti atoll, in the Ellice group, the scene of a deep boring by a committee of the Royal Society of London, as will be told later. "Over the greater part of the lagoon floor . . . there would appear to be a turflike growth of the green calcareous alga, Halimeda. . . . This mass of vegetable matting has a remarkable resemblance to a peat-bog. The upper surface is green and living, but, below, the mass is dead and decaying. The depth of this mass of living and dead vegetable matter appears to be between 60 and 70 feet, and it lies between and around upgrowing bosses of coral rock that form shoals" (Funafuti report, 1904, p. 180).

The walls of the passes which interrupt the continuity of a reef are, like its exterior slope, more or less completely occupied with living corals and other organisms, from which the salient parts, broken off from time to time, must accumulate upon the bottom, while the adhering parts will diminish the breadth of the pass. Thus the passes would eventually be closed in a still-standing reef. Broad reefs with few passes should therefore be regarded as further developed than narrow reefs with many and wide passes.

In the case of reefs that are breached on the leeward side, it may be inferred that the fine sediments on the lagoon floor are slowly but prevailingly drifted in that direction. As a matter of fact, the rimless border of

the floor is there built up to about the same depth of 40 fathoms as that where the gentle slope steepens to the steep pitch on the windward profile of the reef, and presumably for the same reason. Such an outward drift of the finer sediments would seem, as above noted, to retard the aggradation of a lagoon floor; and it is conceivable that the shoaling of good-sized lagoons may be in part thus controlled. In such cases, far from there being a deficiency of sediments for lagoon aggradation, there would be an excess, which is disposed of by exportation. As long as no quantitative measures are available, this view of the problem seems as reasonable as any other. It is in any case probable that the presence of out-drifting sediments in rift breaches prevents the upgrowth of the reef there, where upgrowth would in any case be weaker by reason of a less supply of water-borne nourishment, and perhaps of water-dissolved oxygen also, than on the windward side of the reef circuit. Hence the closing of a breach is probably accomplished, if at all, chiefly by the linear extension of the reef segments that adjoin it rather than by reef upgrowth from the lagoon-floor margin.

Young and Mature Reefs

It thus appears that the long continuation of the processes ordinarily at work upon a coral reef should, if it stands stationary, result not only in closing passes and breaches but also in broadening the reef flat by outgrowth on its exterior slope and by deposition on its interior slope. After the passes and breaches are closed so that no exportation of fine sediments is possible, the lagoon of a still-standing reef would be shoaled and eventually filled. If the original reef were a barrier, the advancing deltas of the central island, the mountainous volume of which is often many times greater than that of the lagoon waters, would aid in converting the lagoon into a plain. Guppy calculated, on the basis of observations made during a visit to Keeling Atoll in the eastern Indian Ocean—the only atoll that Darwin studied—that 5000 tons of detritus are annually washed across the reef flat from the outer face into the lagoon and that at this rate the lagoon will be filled in about 3000 years (1889a, pp. 573, 588; see also Forbes, 1879); but no account was taken of silt exportation.

In view of these possible changes, reefs should be classed not only according to their kind, as fringing, barrier, and atoll reefs, but also according to their stage of broadening, as young and narrow, as mature and broad, and even as old when they are converted into plains. Darwin touched briefly on this view of the evolution of coral reefs; Hedley later treated it in an illuminating manner (1896, p. 17; 1898, p. 174; see also Hedley and Taylor, 1907, p. 407). Maturely broadened reefs are, however, much less abundant than young and narrow reefs; and old reef plains, representing filled lagoons, are known only in the case of very small atolls, unless they are exemplified also by the Bahamas in the West Indies.

FIG. 12

FIG. 13

FIG. 14

FIG. 12—Limestone bluffs fluted by rain rills, Bacuit Bay, Palawan, Philippine Islands. (Photograph by Philippine Bureau of Science.)

FIG. 13—Corniced shore line of a limestone island, west coast of Palawan, Philippines. (Photograph by Philippine Bureau of Science.)

FIG. 14—Elevated reef limestones, dissected, with slightly emerged corniced shore lines; Nateva Bay, eastern part of Vanua Levu, Fiji. (Photograph by Stinson, Suva, Fiji.)

Evidently, therefore, some "renovating agency," as Darwin called it (1842, p. 31), must have acted to maintain reefs and lagoons in their actual forms; and ever since Darwin's time that agency has usually been believed to be the subsidence that he assumed to control reef development. This belief was reasonable, so long as no change in ocean level was considered; but in recent years attention has been directed to the possible rise of ocean level around still-standing islands as an additional control of reef growth, as will be more particularly discussed in Chapter V.

Bank Reefs

In contrast to typical barrier and atoll reefs, which fall off into deep water, mention should be made of what may be called bank reefs, which rise back from the outer margin of rimless shoals. Reefs of this kind will be shown to characterize the marginal belts of the coral seas. If a rock island rises from the center of such a shoal, the reef around it may be called a bank barrier; if the shoal is not surmounted by a central island, an annular reef upon it may be called a bank atoll.

Elevated and Submerged Reefs

Elevated reefs of various kinds are known in fair numbers in the open ocean and are abundant in the unstable region of the Australasian archipelago, where fringing reefs in particular are occasionally found at altitudes of 2000 or 3000 feet or more. In some cases, elevation has been so recent and so rapid that the reef forms are as yet little affected by erosion; but, as limestone is subject to relatively rapid degradation, especially by solution, most elevated reefs are fluted by rain rills and gullies, as in Figure 12, as well as pitted by sink holes and hollowed by caverns; and some are so far dilapidated that their original forms cannot be safely restored. The surface of the older elevated reefs thus gains an indescribable irregularity of surface and is in places impassable because of the sharp and ragged edges, which are destructive to footwear and dangerous to the body, especially to the hands, if one has a fall. The shore line of an elevated reef is usually "corniced" by the water of updashing waves, as in Figure 13. Residual masses often assume mushroom-like forms, as in Figure 14. The steeper slopes of emerged reefs commonly show bare cliffs of massive limestone; but elsewhere the ragged surface usually retains in its cavities enough soil, chiefly the insoluble residue of the dissolved limestone, to support an abundant vegetation. Exploration is thereby made doubly difficult. It is probably for these several reasons that little has yet been learned of the structure and physiography of elevated reefs.

Submerged reefs have been detected by soundings and include fringing-reef benches, sunken barriers, and drowned atolls.

Distribution of Coral Reefs

The limitation of reef-building corals and their associated organisms to the warmer parts of the oceans results in excluding coral reefs not only from the temperate zones but also from the eastern part of the tropical Pacific and from nearly the whole breadth of the tropical Atlantic, where cool currents reach the equator. The great east-west breadth of the tropical and truly torrid Pacific and the abundance of its former and present islands give that ocean the extraordinary number of reefs it now possesses; it is the great coral sea of the world. Its only analogy in the Atlantic is limited to the mediterranean areas of the Caribbean Sea and part of the Gulf of Mexico. The torrid Indian Ocean is rather a sea of banks than of surface reefs; and this ocean is further peculiar in being the only one in which reefs are found on its eastern side, evidently because the short southward reach of Australia deflects a much smaller volume of cool water equatorward than is deflected along the eastern side of the torrid Pacific and Atlantic by the longer southward reach of South America and Africa.

Darwin's chart of the distribution of fringing, barrier, and atoll reefs (1842), although based on all the material he could gather, was necessarily imperfect. Half a century later Guppy (1888) and Agassiz (1903a, Pl. 234) published revised charts introducing many new records; but their interpretation of regions of elevation and subsidence cannot be accepted. More recently a standard series of detailed charts has been prepared by Joubin (1912), showing all known coral reefs by a red tint and distinguishing sea-level reefs from elevated reefs; but the red-tinted areas frequently exaggerate the area of the reefs they represent.

Summary

The facts above presented regarding coral reefs, most of which have been known for the greater part of a century, warrant a number of generalizations. First, coral reefs are the product of congeries of lime-secreting organisms, among which polyps known as corals and algae known as nullipores are the most abundant; the former presumably provide the greatest volume of reef-building material, while the latter are believed to be of essential importance in binding the material together on the reef face so that it shall better withstand the assault of storm waves. The growth of these reef-building organisms is possible only in pure sea water of a relatively high temperature and the corals are usually limited to depths less than 25 or 20 fathoms.

Second, reefs may be initiated on shores of firm rock, free from detritus outwashed from the land; they may also grow up from small depths on submarine shoals, provided firm rock or little-disturbed shells, gravels, or cobbles are present on which the floating embryos of reef-building organisms can attach themselves.

Third, the face of a fringing reef on the shore of a reef-enclosed lagoon is veneered by growing corals for only a few fathoms below the lagoon surface, because its lower slope is cluttered over with detritus which the lagoon waves do not remove in spite of the violence which such waves occasionally attain; but fringing reefs that front the open ocean resemble barrier and atoll reefs in that their exterior growing face extends downward to a greater depth.

Fourth, it is from the growing face of barrier and atoll reefs that detritus is supplied to be swept by waves outward, especially at times of gales and storms, down the gentle slope to the steep pitch, where it is believed to form a talus that descends to great depths; and also inward upon the reef flat and across it into the lagoon. The profile of the gentle slope and the steep pitch is believed to be in adjustment to the action of waves and currents. The growth of a reef as a whole must be much slower than the growth of corals and other organisms on the reef face.

Fifth, the presence of fine detritus, mostly calcareous, on lagoon floors indicates that the large volume of sea water which, surging over the reef flat, drifts slowly through the lagoon and finds exit chiefly through the leeward passes, is not able to dissolve all the detritus and carry it away in solution. Hence lagoon floors suffer aggradation rather than excavation. The occasional disturbance of the lagoon waters by storm winds appears to cause a fairly equable distribution of fine detritus over lagoon floors, as well as to drift the finer sediments toward the leeward breaches in the reef and to export the finest sediments to deep water.

Sixth, reefs are usually of more continuous growth on the windward than on the leeward arc of their circuits; this is believed to be because the reef-building organisms on the windward side are constantly receiving a good supply of food and of oxygen in the on-drifting ocean water, while on the leeward side the supply of food and oxygen is somewhat depleted; also because only clear ocean water comes to the reef on the windward side, while much fine detritus is drifted toward the leeward side.

Seventh, it is to be inferred from the above generalizations that new fringing reefs will be formed on any new shore line where fitting conditions for reef attachment and growth are provided; that a reef thus formed will increase in breadth by outward growth on a stationary coast; that it will increase in thickness by upgrowth on a slowly subsiding coast; and that, if the upgrowth be vertical or outward, the fringe will separate itself from the receding shore and become a barrier reef. On the other hand, the growing face of a reef will migrate down the slope of a slowly rising coast. But it is also to be inferred that a rapid or sudden subsidence may submerge a reef to such a depth as to "drown" the reef-building organisms, whereupon a new fringing reef may be formed at the level where the shore line thereafter rests; and, on the other hand, that a rapid or sudden upheaval will cause the emergence of a reef, after which a new fringing reef may be formed on the exterior slope of the emerged reef.

CHAPTER II

DARWIN'S THEORY OF UPGROWING REEFS ON INTERMITTENTLY SUBSIDING FOUNDATIONS

The Debatable Origin of Coral Reefs

Narrow fringing reefs may be reasonably accounted for as formed on a previously reef-free coast by new colonies of reef-building organisms, as has already been explained. Barrier reefs and atolls are of more uncertain origin, and during the earlier period of Pacific exploration many more or less fantastic theories, well reviewed by Böttger (1890), were proposed to account for them. Not until it was learned that reef-building corals thrive only at moderate depths, ordinarily less than 25 fathoms, have coral reef theories been more reasonably restricted. There is, however, still much debate concerning them.

Indeed, if the visible reefs alone are examined it is impossible to determine whether they have been formed by upgrowth on still-standing, aggraded submarine banks, as Rein first and Murray later suggested and as Wood-Jones still more recently argued; by outgrowth from still-standing foundations, the lagoon being excavated by solution back of the living reef, as Murray also proposed; by outgrowth on rising foundations, as Semper and Guppy believed, Semper having anticipated Murray in explaining lagoons by solution; by upgrowth on still-standing foundations completely truncated by abrasion, as Wharton proposed; or incompletely truncated, as Tyerman and Bennet long ago and as Guppy later suggested; or on platforms produced around still-standing foundations by subaerial erosion and submarine denudation, as Agassiz believed; or on still-standing foundations abraded by the lowered Glacial ocean and submerged by the rise of the Postglacial ocean, as Daly argues; or as a rule by upgrowth on intermittently subsiding foundations, as Darwin taught—for all these theories succeed in explaining the visible features of reefs that they were invented to explain. It is with regard to the invisible conditions and processes of the past that the theories differ. As those conditions and processes cannot be determined by observation, they must be learned by inference; and the inferences of different observers vary greatly, as has just been indicated. Observation of existing facts is of course fundamental; yet no less essential in reaching the solution of such a problem as the origin of coral reefs is the very different process of penetrating by means of logical thinking far beyond the limits of possible observation, and thereby safely crossing the wide field of speculation.

Many pages in Part I of this volume will therefore be given to the discussion of various theoretical schemes, together with their assumed postulates and their deduced consequences, in order that each scheme shall be clearly and fully conceived. At the same time a limited selection of confirmatory or contradictory facts will be presented, in order that each scheme shall be given at once a preliminary test or verification. We shall thus be prepared, when the facts of the problem are more fully brought forward in Part II, to learn which one of various theories of coral reefs, or what combination of several theories, best deserves to be accepted as giving a true counterpart of the march of natural events in their passage from the imagined conditions and processes of the past to the observed conditions and processes of the present.

The solution of the coral reef problem has been delayed because of the partial and often crude manner in which it has been treated; partial in that the alternative hypotheses, proposed by various observers who rejected Darwin's theory, were based upon the study of too small a variety of reef-encircled islands or in that they were constructed upon too limited an understanding of the many factors that enter the problem; and crude in that, although the logic of scientific analysis has long been well understood among logicians, it has been too often ignored in this problem both by exploring investigators in the coral seas and by teaching investigators at home. In a word, the method of attacking the coral reef problem has not been standardized.

The Nature of Geological Theories

Inasmuch as the coral reefs of today are the product of processes that have acted in the past, it is manifest, as above noted, that those processes cannot be discovered by observation, for the past is unobservable. They can be discovered only by making inferences, which being based on observed present-day facts will, it is hoped, prove to be the true counterparts of the past processes by which the present facts have been brought into being. When such inferences take on a more or less definite form and thus seem to their inventor to lead him reasonably through the past to the present, he calls them a theory; and the question then arises: How can it be learned whether the theory is true? In attempting to answer this question, it should be noted, first, that the theory is based on a number of assumed conditions or postulates which are taken to represent the initial stage from which the processes of the theory advance; and second, that the theory in its original form, as first conceived or invented, is seldom more than a mere outline of the whole sequence of conditions and processes which, if the theory be true, have really led up to the present facts. It is thereupon the inventor's duty to scrutinize his postulates carefully, in order to assure himself of their validity, and to expand his inferences logically, with the object of filling in the outline of his theoretical scheme un-

til it shall be as complete as he can make it. Not until both these tasks are completed is it possible to pass an assured judgment as to the correctness of a theory, in the sense that it truly—or better said, with very high probability—represents the invisible facts of the past.

It is not enough that the theory in its simple initial form shall explain the facts that it was invented to explain; indeed, unless it is competent to meet that preliminary test, it should be discarded at once as worthless. It must do more: its additional elements, not perceived when it was invented, must be proved to be the true counterparts of additional facts not previously in mind, perhaps not then even discovered. The formulation of these additional elements of the theory is accomplished in geological investigation by the mental process of deduction, which, proceeding in a more orderly manner than invention, attempts to work out all the possible consequences of the theory, with particular attention to those consequences that may be today visible. Then these consequences, as clearly defined as may be, are to be confronted with the facts, old and new; if they survive this confrontation, the theory is confirmed. If the deduced consequences not only meet successfully all the facts that were known when the theory was invented and all the facts that are later found by wandering exploration, but if they serve also as guides to the discovery of new facts of a well specified kind, then the theory is particularly well recommended. It is still further strengthened if it makes possible the prediction of the occurrence of previously unknown facts.

If a problem embraces but a few facts, it may be difficult to demonstrate the correctness of a theory that is proposed to account for them; for in such a case no sufficient number of additional facts can be found by which the theory may be duly tested. But when the facts of a problem are numerous and varied, as is the case with coral reefs, and when the consequences of a theory that is proposed to explain them are successful in meeting all previously known facts and also many additional facts of later discovery, and when the consequences even serve to predict the occurrence and thus lead to the discovery of previously unknown facts; and, furthermore, when such a theory is thus found to be successful not only by its inventor but also by other investigators working independently in various parts of the world, its correctness becomes probable in so high a degree that it must be accepted as true.

The review of various coral reef theories in this and the next three chapters will attempt to make application of the above-outlined principles. It will then become apparent that the double task of deducing consequences and of confronting them impartially with the appropriate facts has been too often neglected. As a result credence has been given to certain theories which, when more critically examined, are found to be of little value. But it will also appear that one of the theories, which was little more complete in its first-invented form than its competitors, is extraordinarily fertile in yielding deducible consequences that were undreamed

of by its inventor; and that these consequences are marvelously successful in their confrontation with the facts, many of the facts having been, like the deduced consequences, wholly unknown at the time the theory was invented. Naturally, it is to that theory that confidence must be given.

Postulates and Consequences of Darwin's Theory

The most famous and for some thirty or more years the universally accepted theory of coral reefs was proposed by Darwin ninety years ago. It does not particularly specify the conditions under which fringing reefs are first established on a pelagic island, but it develops barrier reefs from fringing reefs and atolls as a rule from barrier reefs by upgrowth on intermittently subsiding foundations of whatever form, while the enclosed lagoon floors are smoothly aggraded by deposits of inwashed and locally formed sediments. Darwin made the first announcement of this theory in a brief and incomplete article, soon after his return from the Pacific (1837); a second and somewhat more extended statement is included in his "Journal of Researches" on the *Beagle* (1840, pp. 554–569); a third statement was given detailed inductive presentation in his admirable book on "The Structure and Distribution of Coral Reefs" (1842), to the preparation of which he devoted several years. A second edition of this book was published in 1874, with references to new observations by others but with few changes in its theoretical views. A third edition was published in 1888, after the author's death, with notes by Bonney. Quotations given below simply by page number refer to the first (1842) edition.

It should be remembered, when the above-named books are examined, that their author, Charles Darwin, was a young man, but little over thirty years of age when he wrote them, and that he was well under thirty years of age and without previous experience in exploration, when he set out in the *Beagle*, a small sailing vessel under command of Captain—later Admiral—Robert Fitzroy, on a surveying voyage around the world. He was not one of the official staff but was entered in the "list of supernumeraries" as Fitzroy's guest, for he paid his share of the mess and was free to withdraw at any time if he wished to do so. In spite of repeated distress and suffering from seasickness, in consequence of which his health was impaired for many years afterwards, he persevered to the end. He was described by his captain at the beginning of the voyage as "a young man of promising ability, extremely fond of geology, and indeed of all branches of natural history" (1839, p. 19) and at the close of the voyage as having "willingly encountered the discomfort and risk of a long cruise in a small and loaded boat." His simply written "Narrative" still holds an assured place in scientific literature as the plain and truth-telling record of facts noted by an observant and thoughtful mind in novel surroundings. Few "supernumeraries" have ever contributed more valuable results to the undertaking on which they embarked.

The Fundamental Postulate of Intermittent Subsidence

Darwin's fundamental postulate of slowly subsiding foundations, on which upgrowing reefs maintain their crests at sea level, was not limited by any specifications as to the form that the foundation should possess; the opinion of some recent writers that islands previously abraded into cliff-and-platform profile were excluded has no sufficient ground. True, only a single pattern of island profile, that of Borabora in the Society group, was represented in Darwin's diagrams, a narrow limitation of type being there a necessary consequence of the use of graphic in contrast to verbal presentation; but the profile selected for representation was well warranted because it is typical of many reef-encircled islands. On the other hand his text was broadly general. He clearly understood (pp. 98, 99, 102) that any kind of coast, insular or continental, sloping or cliffed, along the shore of which a fringing reef might be established, would serve as a fitting foundation for the upgrowth of a barrier reef if the coast subsided.

Darwin's deductions of the consequences following from different rates and amounts of subsidence are also well carried out, as far as reefs are concerned. He soon introduced two variations into his scheme, first by considering changes in the rate of subsidence in the phrase, "as the island sinks down, either a few feet at a time or quite insensibly"; and next by suggesting the occurrence of still-stand pauses in the phrase, "the lagoon-channel will be deeper or shallower, in proportion to . . . the rate of subsidence and the length of the intervening stationary periods" (p. 99). The accumulation of sediments in the lagoon, outwashed from a central island or inwashed by waves from the reef, is repeatedly referred to; the possible loss of a considerable quantity of fine sediments by outflowing currents through the passes in the reef is noted (p. 29); the smoothness of the lagoon floor is emphasized and ascribed to aqueous deposition (p. 26); and the effect of a long stationary period in permitting a lagoon to be nearly filled up with sediment is duly mentioned (p. 102). All these points will be here more fully discussed on later pages. The unlike consequences of more recent and of less recent subsidences are later specified, the first case being illustrated by the island of Vanikoro, in the Santa Cruz group of the western Pacific, and the second case by certain members of the Society group (p. 128).

A long pause in subsidence is inferred from the three-mile breadth of the reef of Christmas Atoll in the central Pacific (pp. 74, 75), not to be confounded with the high-standing Christmas Island in the eastern Indian Ocean. Similarly, on the atoll of Diego Garcia in the central Indian Ocean, "the broad annular strip of land, formed by the continued accumulation of detritus, shows how long this atoll has remained at its present level" (p. 70). Reef widening by outgrowth during pauses in subsidence is therefore inherently a part of Darwin's theory.

A highly significant passage, presented before the theory of subsidence is outlined, reads as follows: "It is very remarkable that not one instance, as I believe, is known of a moderate-sized lagoon being filled up. . . . We cannot suppose that the many atolls in the Pacific and Indian oceans all have had a late origin, and yet should they remain at their present level, subjected only to the action of the sea, and to the growing powers of the coral, during as many centuries as must have elapsed since any of the early tertiary epochs, it cannot, I think, be doubted that their lagoons and the islets on their reefs would present a totally different appearance from what they now do. This consideration leads to the suspicion that some renovating agency (namely subsidence) comes into play at intervals, and perpetuates their original structure" (p. 31). To this well considered statement another may be added: "The conclusion to which I am finally led . . . is that the atolls of the Low Archipelago [Paumotus] have, like the Society islands, remained at a stationary level for a long period: and this is probably the ordinary course of events, subsidence supervening after long intervals of rest" (p. 130). But be it noted that these "long intervals of rest" are only long enough for small changes in reefs and lagoons: they are not long geologically. It is because of the frequent recurrence of this idea (pp. 104, 107, 126, 145) that in the heading of the present chapter I have used the phrase "upgrowing reefs on intermittently subsiding foundations," and not simply "on subsiding foundations."

Darwin's Views on Fringing Reefs

Fringing reefs, the kind of reef "which alone offers no difficulty in explanation of its origin" (p. 98), were as a rule taken by Darwin to have been formed on stationary or rising coasts (pp. 131, 137), regarding the earlier history of which little inquiry was made. Hence, the numerous fringing reefs that have been since found on coasts of submergence might be regarded as invalidating the subsidence theory, were it not that an alternative explanation, which has very generally been overlooked, was clearly stated by Darwin himself in the discussion of the consequences of subsidence at a more rapid rate than that of reef upgrowth: "If during the prolonged subsidence of a shore, coral-reefs grew for the first time on it, or if an old barrier-reef were destroyed and submerged, and new reefs became attached to the land, these would necessarily at first belong to the fringing class" (p. 124).

Few writers of later date have given attention to the formation of fringing reefs in this way, which may be illustrated in Figure 15. Dana's nearest approach to this point seems to be a brief statement in which he noted that "abrupt subsidences of only 120 feet would put reef corals below a surviving depth and so lead to the beginning of a new reef" (1885, p. 97). At a little earlier time Chantérac, a French naval officer otherwise unknown in coral reef literature, had briefly noted, apparently in ig-

norance of what Darwin had written on this special topic, that if one fringing reef is drowned by rapid subsidence, another will be formed at a relatively higher level on the new shore line (1875, p. 635).

Numerous and excellent examples of fringing reefs on embayed shore lines of submergence are found in the Philippine Islands, the marginal features of which are well shown on the charts published by the U. S. Coast and Geodetic Survey; for instance, on the extraordinarily embayed northwestern coast of Palawan, the southwesternmost member of the ar-

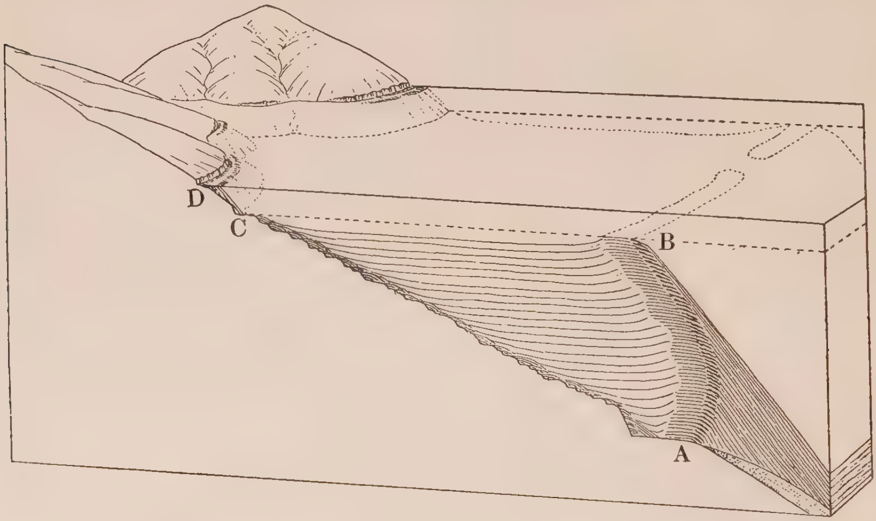


FIG. 15—Block diagram of a rapidly submerged barrier reef and a narrow fringing reef of a new generation on the new, wave-cut shore line.

chipelago: here what seems to be a previously formed barrier reef and its aggraded lagoon floor now constitute a broad submarine bank with a rising rim, described in two of my earlier papers (1918a, p. 199; 1918c, p. 515) and here considered in a later chapter. The fringing reefs of such a coast may be described as of a "second generation." It is interesting to note that Darwin interpreted certain accounts of the Philippine Islands as indicating that the fringing reefs that occur there had been formed on rising coasts, and he therefore colored these islands red on his chart. That recent elevation has taken place in certain places is proved by the occurrence of emerged reefs of well preserved form; but that the fringing reefs at present sea level have all been formed after a movement of elevation is improbable.

Examples of fringing reefs on embayed coasts of submergence are also found around Tutuila in Samoa, around Fauro, a small island in the northwestern part of the Solomon group, and on the Seychelles in the Indian Ocean, as I have elsewhere pointed out (1918c, p. 524). They all support Darwin's theory. It must not be overlooked, however, that bold coasts which have been first submerged and then partly emerged, will still be embayed; and that if fringing reefs become attached to them, such

fringes will belong with those described by Darwin as formed on rising coasts. Australasian examples of this kind appear to occur in Celebes and Halmahera, according to the observations of the Sarasins (1901), Ahlburg (1913), and Abendanon (1917).

In order to avoid misunderstandings, let it be here again explained that, as already briefly stated, Darwin included certain offshore reefs, two or three miles from the shore, in his chapter on fringing reefs (1842, pp. 52, 56), apparently because the lagoon enclosed by them is shallow; thus suggesting that they did not owe their opportunity for growth to the subsidence

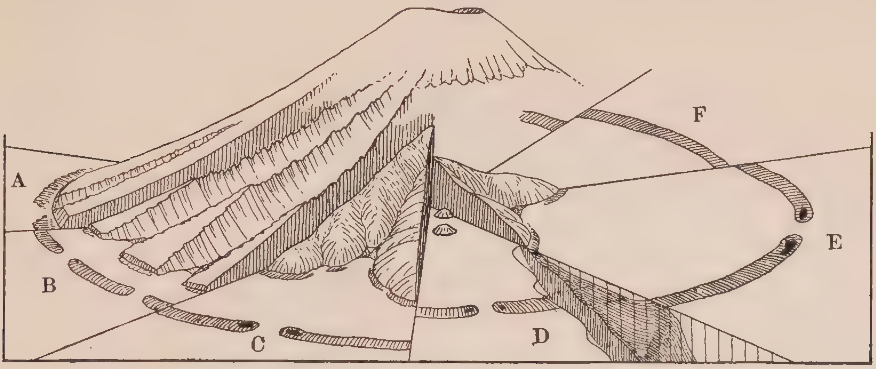


FIG. 16—Sector diagram illustrating the upgrowth of a reef around a subsiding island.

of their foundation. Inasmuch as it is eminently possible that reefs of this kind may have been initiated as true, near-shore fringes, previous to a moderate submergence by which their present distance from shore has been determined, Darwin's inclusion of such reefs with fringes does not seem fully warranted. They will be here called bank reefs.

Barrier Reefs under Darwin's Theory

If subsidence takes place at a slow rate, a previously established fringing reef, sector *A*, Figure 16, may grow upward while the shore of the diminishing island recedes behind it. The fringe will thus become a barrier reef, as in sectors *B*, *C*, *E*. In the meantime, new fringes will be continually formed along the receding shore line at higher and higher levels, as the lagoon encroaches more and more upon the slope of the subsiding reef foundation; but, apparently in consequence of the enfeebled growth of corals and their associated organisms in the lagoon waters, the new fringes do not as a rule grow up to form new barriers but sidle retrogressively up the slope and hold to the shore. A few examples, however, of double barriers are known; one in Fiji has been shown in Figure 7; another, now elevated above sea level (Fig. 195), is charted at the eastern end of the island of New Georgia in the Solomon group. The interior member of these exceptional double barriers is probably an upgrowth from a mid-level fringe of unusually flourishing condition.

Darwin explicitly recognized that according to his theory "the vertical thickness of . . . barrier coral reefs is very great" (p. 47), as is shown in section on the near side of sector *E*, Figure 16. He also noted that the existence of lagoons "often between 200 and 300 feet deep," enclosed by a barrier reef "at a distance of two, three or more miles from the shore . . . utterly precludes the idea of the reef having grown outwards" on a stationary foundation. He favored the idea of its having grown upward from a

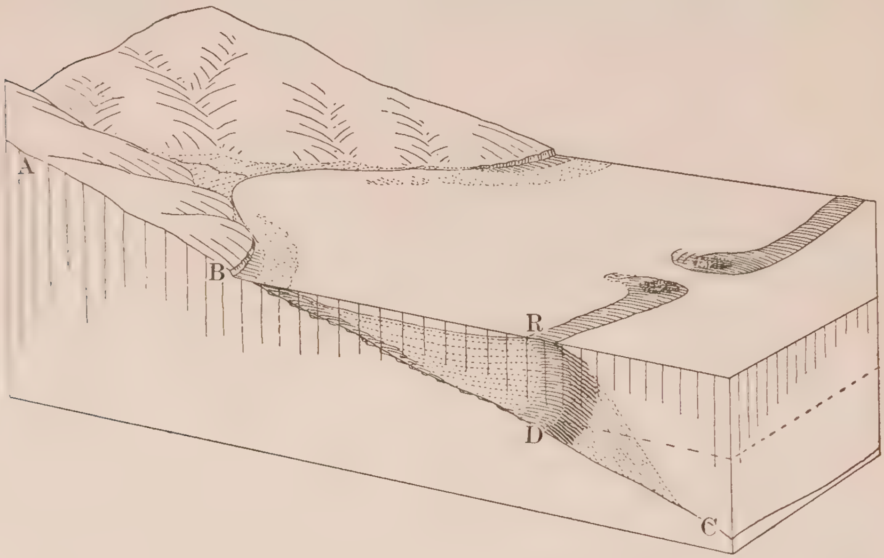


FIG. 17—Block diagram of a barrier reef developed by upgrowth of a fringing reef over a subsiding island. The thickness of the barrier reef, *DR*, is inferred by prolonging the visible slope of the island, *AB* under the reef, *DC*.

subsiding foundation (p. 49), because there is no reasonable way of excavating lagoons to so considerable a depth behind an outgrowing reef; and in this view as to the non-excavation of lagoons he is supported by many modern studies. Even some of those observers who have rejected Darwin's theory as not generally applicable appear to have accepted it for barrier reefs enclosing deep lagoons. Thus Sir Archibald Geikie, in a notable address in which he concluded that the theory of subsidence no longer generally holds good for the explanation of coral reefs, stated that it might still apply to reefs enclosing lagoons 40 or more fathoms in depth (1883-85, p. 27). Guppy, an experienced student of coral reefs, also said: "It is the depths of from 35 to 60 fathoms which are found occasionally within both barrier reefs and atolls that lend the greatest support to the theory of subsidence" (1884–86, p. 887). Let it be stated, however, that the floor of a lagoon is aggraded by an unmeasured thickness of sedimentary deposits, and therefore its depth gives too small a measure of the foundation depth from which the enclosing reef has grown up.

Darwin himself had a clear understanding of this phase of his problem;

he said that the submarine profile of an island "probably does not widely differ in inclination from the actual submarine prolongation of the land." By drawing inferred profiles for several islands, he estimated the depth of their barrier-reef foundations to be as much as 1200 or 2000 feet (pp. 47, 48). Dana had a similar understanding of the problem (1849, p. 47). A reasonable inference as to the depth of a reef foundation may truly be made by prolonging the supermarine slope, *A*, *B*, Figure 17, of a reef-bordered

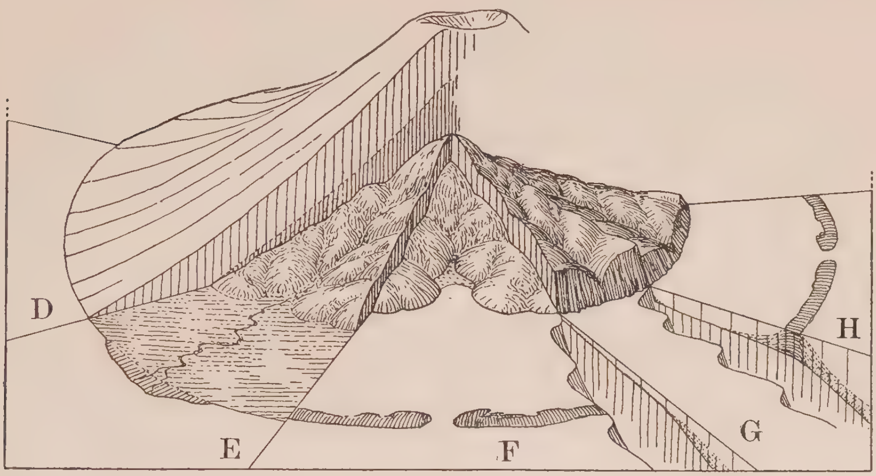


FIG. 18—Sector diagram of an imagined volcanic island having a resistant core and a weak cover in successive stages of its erosion, abrasion, and subsidence.

coast beneath sea level until it reaches a point, *D*, below the reef, *R*; but in doing so, due attention should be given to the geological structure of the coast and to its physiographic development. This is well illustrated by the case of Tahaa, in the Society group, as will be shown in Chapter XIII.

For a continental coast, such as that of northeastern Australia, the same method may be applied, although its application there is more complicated because of the intricate physiographic history of that coastal slope, as deciphered by Andrews (1900–04). It is only by the most arbitrary assumptions, in which the physiographic development of the coastal highlands there occurring is wholly disregarded, that a small depth can be assigned to this reef, as I have elsewhere shown (1917b) and as will be further explained later. The southwestern coast of New Caledonia similarly suggests great depths for the foundation of its far-removed barrier reef, as will also be set forth in the sequel.

On the other hand, it is easy to imagine that if an island were composed of a core of resistant rocks and a cover of weak rocks, as in Figure 18, sector *D*, the weak cover might be worn down to a lowland while the resistant core was only maturely dissected, as in sector *E*; and if submergence then took place an offshore barrier of small thickness might grow up, as in sector *F*. But unless the island had been reef-protected during its degrada-

tion, abrasion would presumably act faster than subaerial degradation; the weak cover would therefore be cut down to a submarine platform and the margin of the resistant core might be cliffed, as in sector *G*. If a moderate subsidence next took place a distant barrier reef of small thickness might grow up from the outer part of the aggraded platform, as in sector *H*; but the island cliffs might still be partly visible and the shore line would be little embayed if at all. In order that the central island should be well embayed and not cliffed after the barrier reef is formed around it, as in sector *F*, it should have been reef-protected during the removal of its weak cover; but that could hardly be the case unless the cover were largely calcareous, so that it might be removed chiefly in solution. Otherwise, the outwash of detritus from the rapidly degraded surface would exclude a protecting reef and abrasion would then accompany degradation.

Two islands of composite structure have been described, the weak cover being calcareous in both cases; hence both were probably reef-protected while the cover was degraded. One is St. Croix in the Lesser Antilles, which consisted before its elevation of a core of resistant stratified rocks and a cover of limestones, probably the lagoon beds of an earlier barrier reef; the limestone cover is now since elevation worn down to low relief, while the hard-rock core is still submountainous. Here a small subsidence would, according to Vaughan (1919, p. 258), submerge the lowland and permit the upgrowth of an offshore barrier reef of small thickness. The other island is Vanua Mbalavu in eastern Fiji, which I have described (1915b, p. 251; 1916c) as consisting of a volcanic core and a limestone cover; here it seems that not only the greater part of the limestone cover has been worn down to low relief but that a moderate subsidence accompanied by barrier-reef upgrowth has occurred since then. In such cases as these the breadth of a lagoon does not give any valid indication of the depth of the barrier reef that encloses it but only, as Vaughan has well said, an indication of the stage and the area of degradation of the weaker rocks.

But it would be gratuitous to suppose that all the volcanic islands of the Pacific which are now encircled by barrier reefs have had a composite structure and a degradational history of the kind just described. For most of them, if not for all, the inference of deep reef foundations holds good. It may therefore be urged that the great thickness of barrier reefs demanded by Darwin's theory is made perfectly reasonable by the examples above cited and by many others of a similar nature.

The Moderate Thickness of Elevated Reefs

The moderate thickness of many elevated reefs, particularly those found in the Australasian archipelago, has been cited to show that the great thickness demanded for barrier reefs by Darwin's theory is unwarranted; but the true lesson that such elevated reefs teach is quite different. Imagine, for example, an embayed coast on which a sea-level fringing reef,

BB, Figure 19, and two elevated reefs, *C* and *D*, are found. The fact of the coast's being embayed shows that it was formerly more emerged than at present; the shore line may therefore have stood at *AA* while the now embayed valleys were eroded; and the shore was then presumably reefless and cliffed, because of the great quantity of detritus discharged upon it. The high-level fringing-reef terraces show that, since the shore line stood at *AA*, it has been shifted, with pauses at *B*, *C*, and *D*, though not neces-

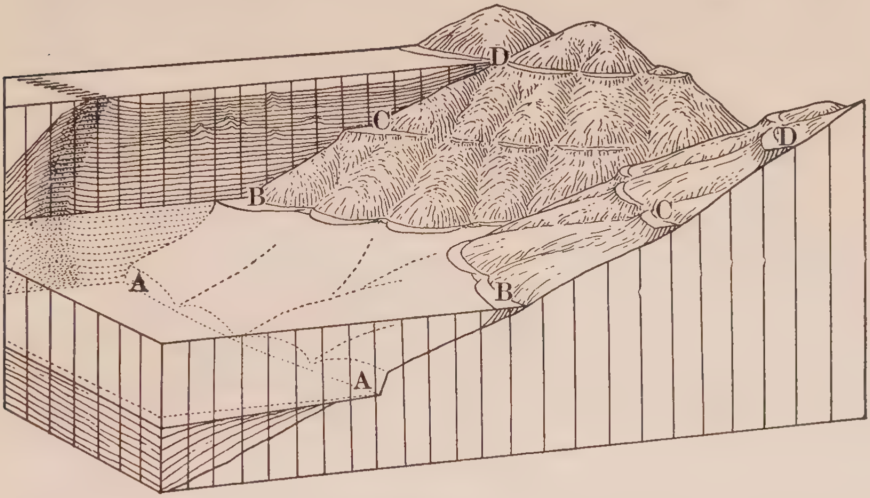


FIG. 19—Block diagram illustrating the effects of rapid subsidence and elevation, as inferred from unconformable fringing reefs, *C*, *D*, *B*. A heavy barrier reef in the background illustrates the effect of slow subsidence.

sarily in that sequence; and the fact that the reefs *C* and *D* are now elevated shows that the subsidence which placed the shore line at *D* has been reversed to upheaval. Reef *B*, standing at present sea level, has probably been formed since the shore line assumed its present position, presumably in consequence of island upheaval. Reef *C* may have been formed during a pause either in the preliminary subsidence or in the following upheaval. The highest reef, *D*, was probably formed during a still-stand pause when upheaval was about to replace subsidence. Finally, the formation of the several reefs separately at different levels can only mean that the movements of subsidence, by which the shore line was shifted from *A* to *D*, were as a rule too rapid to be compensated by reef upgrowth. Had all the subsidence been slow, a great barrier reef as thick as the whole measure of subsidence would have been formed, as in the background block of the figure. Hence, thin elevated reefs resting uncomfortably on the underlying rocks over an embayed shore line, as is repeatedly the case in Australasia, far from teaching that Darwin's theory as to barrier reefs is in error, really bear witness to the correctness of his view that great subsidence may take place, and also to the correctness of his explanation of fringing reefs of a second generation on rapidly subsiding coasts.

A corollary of the above conclusion is that whatever subsidence has taken place in the atoll region of the Pacific must have been much slower than the movements of the Australasian islands; for otherwise the Pacific atolls could not have maintained their crests at the sea surface.

Another misapprehension of Darwin's argument is also refuted by the facts just cited; namely, that he was unreasonable in assuming that subsidence commonly took place at a rate not too rapid for compensation by reef upgrowth; for he made no such sweeping assumption. He truly enough wrote: "The rate of subsidence has not ordinarily exceeded that of the upward growth of the massive corals"; and this might have been better stated as the rate of reef upgrowth. But the context makes it clear that the statement applied only to regions where reefs have been successful in keeping their crests at sea level. On the other hand, he recognized very clearly that more rapid subsidence may occur in other regions with the result of submerging barrier reefs, which will then be succeeded at higher levels by new fringing reefs as above told, or with the result of completely drowning atolls. The islands of the Australasian archipelago have repeatedly suffered rapid and diverse movements of this kind, and it will be made clear in the sequel that the almost complete absence of well developed barriers and the relative rarity of well formed atolls in that very unstable region are due precisely to the fact that its movements have frequently been so rapid that they could not be counterbalanced by reef upgrowth.

Darwin on the Origin of Atolls

Darwin explained atolls as ordinarily derived in the most natural manner from upgrowing barrier reefs after their central island had disappeared by subsidence, as in sector *F*, Figure 16; but he also gave open-minded and impartial consideration to various other methods of atoll production. He said: "If the rim of a crater offered a basis at a proper depth, I am far from denying that a reef like a perfectly characterized atoll might be formed; some such, perhaps, now exist; but I cannot believe in the possibility of the greater number having thus originated," because "on this view the volcanic action must be supposed to have formed . . . a vast number of craters, all rising within a few fathoms of the surface and not one [in so far as atolls are concerned] above it" (pp. 89, 94). Lyell was convinced by this fair-minded presentation of the case; he wrote to a friend: "I must give up my volcanic crater theory forever, though it cost me a pang at first, for it accounted for so much. . . . All went so well with the notion of submerged, crateriform and conical volcanoes. . . . Yet in spite of this the whole theory is knocked on the head, and the annular shape and central lagoon [of atoll reefs] have nothing to do with volcanoes, nor even with a crateriform bottom" (Life and Letters of Sir Charles Lyell, London, 1881, Vol. 2, p. 12).

Darwin furthermore suggested several other possible conditions of atoll formation and gave good reasons for not regarding them as prevalent. He

thought the supposition that islands of any kind "may have been elevated, but that as soon as raised, the protuberant parts were cut off by the destroying action of the waves" cannot be accepted, because "the upheaval and subsequent abrasion of an island would leave a flat [and shallow] disc, which might become coated with coral, but not a deeply concave surface" or lagoon floor (p. 93). Similarly, "the supposition that craters were at different times upraised above the surface, and were there abraded by the surf and subsequently coated by corals is subject to nearly the same sort of objections" (p. 94). The young naturalist of the *Beagle* was indeed much nearer the truth in thus limiting the work of abrasion by waves at normal sea level to the production of a shallow platform than Wharton was many years later (1894, 1897) in implying that normal abrasion could produce rock platforms for atolls 20 or 30 fathoms or more below sea level.

Darwin also saw that if "corals were to grow up from a bank with a level surface some fathoms submerged, having steep sides and being situated in a deep sea, a reef not to be distinguished from an atoll, might be formed"; and he believed "that some such exist in the West Indies" (p. 89). He recognized too that "a bank either of rock or of hardened sediment, level with the surface of the sea, and fringed with living coral, would . . . by subsidence be immediately converted into an atoll, without passing, as in the case of a reef fringing the shore of an island, through the intermediate form of a barrier reef. If such a bank lay a few fathoms submerged, the simple growth of the coral without the aid of subsidence, would produce a structure scarcely to be distinguished from a true atoll." But he added that "the larger groups of atolls in the Pacific and Indian oceans cannot be supposed to be founded on banks of this nature" (pp. 101, 102), probably because he knew of no adequate means of producing such banks.

Depth of Lagoons within Upgrowing Reefs

The aggradation of reef-enclosed lagoon floors by sediments derived from various sources has already been mentioned. Darwin assumed that the rate of such aggradation, like that of reef upgrowth, was not much exceeded by the rate of subsidence (p. 115); and surely, if any subsidence takes place at all, this assumption must be warranted with respect to the upgrowth of the reefs at least; otherwise they would not be present. Whether the assumption can be true also for the rate of lagoon-floor aggradation, particularly in the case of large atolls, where the supply of sediments comes largely from organisms living in or at the bottom of the lagoon waters, is not so manifest; but there is nothing known that contradicts it.

It is important to note that the rate of subsidence must be understood to be not faster than the rate of *reef* upgrowth rather than of *coral* upgrowth, because, as has already been pointed out, a considerable share of coral upgrowth has to be sacrificed in building up other parts of the entire

reef structure than the growing reef face; namely, the sea-level flat and the lagoon floor back of the reef and the submarine talus outside of and below it.

Atolls Drowned by Rapid Subsidence

Although the subsidence of reef foundations cannot have been faster than reef upgrowth where sea-level barrier reefs and atolls are found, it is eminently possible that subsidence may elsewhere proceed more rapidly. Then, parallel to the case of barrier reefs that are drowned by rapid submergence as above explained, will be that of atolls similarly drowned, except that, as they have no central island, the submergence will be complete. This aspect of the problem was more deliberately considered by Darwin than that of new fringing reefs on coasts of submergence, and it has also been more generally apprehended. He wrote: "There is nothing improbable in the death from the subsidence being great or sudden, of the corals on the whole, or on portions of some of the atolls. . . . Further subsidence, together with the accumulation of sediment, would obliterate its atoll structure [form], and leave only a [rimless] bank with a level surface" (pp. 108, 107). The Great Chagos bank, or drowned atoll, in the central Indian Ocean was instanced as a consequence of such subsidence; many other similarly submerged atolls are now known.

If Darwin's explanation of drowned atolls and rimless banks in the coral seas be correct, it might be expected that they would not be distributed haphazard but that they would occur in groups, as sea-level atolls commonly do, and in such relation to areas of sea-level reefs as would be consistent with the broad deformations that supposedly affect the ocean floor. The same would be true of elevated atolls and other reefs; they should be similarly distributed with relation to sea-level reefs. Both of these expectations are realized in a fair degree. It is true that isolated examples of elevated atolls occur: witness Niue, between the Tonga and the Society group, and Christmas Island in the eastern Indian Ocean; but these are both lonesome islands; no others are near by to indicate the extent of the movement of upheaval suffered by the ocean floor. On the other hand, a number of the northwestern Paumotu atolls in the east-central Pacific are slightly elevated; and a group of banks of fairly uniform depths has been discovered since Darwin's time to the north of Fiji, for which I have proposed the name, Darwin Hermatopelago or Sea of Banks. The groups of banks in the western part of the Indian Ocean are also noteworthy in this respect.

Inferences as to Coral Reef Structure

As a preliminary to what follows, it should be recalled that Darwin held the opinion now generally current that the limit down to which reef-building corals can grow is influenced by freedom from sediment as well as by depth of water (p. 84); and he concluded that "in ordinary cases, reef-

building polypifers do not flourish at greater depths than between 20 and 30 fathoms" (p. 86). Reference may be here again made to his belief that, because of the similarity in the exterior slope of many reefs, "the angle of inclination must result from an adaptation between the growing powers of the coral, and the force of the breakers, and their action on the loose sediment."

As if in deference to that prejudiced view of scientific investigation which attributes a low value to the deductive side of a theoretical inquiry, Darwin placed several important deductions concerning reef structures in a small-type footnote at the end of one of his chapters. These deductions include, among others, the unlike make-up of a reef proper "formed by the upward growth of coral during successive subsidences," and of the enclosed lagoon deposits (pp. 116, 117). After elevation, the horizontal strata "which were formed within the lagoons . . . would more often be preserved to future ages, than the exterior solid reef," which would be first removed by denudation (p. 118).

The importance of these theoretical considerations may be judged by noting that the possible great thickness, the prevailing fine texture, and the horizontal attitude deduced for sub-lagoon beds enclosed by upgrowing barrier reefs on subsiding foundations, contrast strongly with the coarse texture and steeply inclined sub-lagoon beds as demanded by theories of outgrowing reefs on still-standing foundations; and also with the small thickness of horizontal lagoon beds lying on truncated volcanic rocks as demanded by theories of veneering reefs on still-standing abraded foundations. It is only after deducing and clearly defining these contrasts that an observer will be competent to detect the correct theory of reef formation when uplifted reefs are studied.

The Distribution of Coral Reefs

It was at the close of his well-balanced discussion of the unlike consequences following from the theory of intermittent subsidence and from various other theories, that Darwin gathered together in an appendix of 50 pages all records available at the time regarding the occurrence of different kinds of reefs, for the purpose of mapping their distribution. He did not "venture to hope that the map is free from many errors," as he had to seek "information from all kinds of sources" (p. 123); but he regarded it as approximately correct, because the several kinds of reefs "produced under widely different conditions, are not indiscriminately mixed together" (p. 124). Exception has been taken to this conclusion, because of the association of the various kinds of reefs in certain island groups, as is the case in the Pelew and the Fiji Islands; but, while it is true that the phenomena to be explained are thus shown to be more complicated than they are represented on Darwin's map, they may nevertheless be easily accounted for by that extension of his theory which recognizes that "some

of the same islands have both subsided and been upraised" (pp. 145, 146), as is further explained below.

Darwin charted not only the various kinds of coral reefs but also the volcanoes now active or known to have been active in historic times; he colored the atolls dark blue; barrier reefs, light blue; and fringing reefs, elevated reefs, and active volcanoes, red. Records then available were in many cases not clear as to the kind of reefs that were described, and all uncertain cases were left uncolored: "I am determined to err on the cautious side," the young naturalist wrote (p. 154). The much fuller accounts of various reefs gathered in later years show that a good number of uncolored examples might be now safely colored as almost-atolls or atolls. Thus the little Clipperton almost-atoll at the far northeastern margin of the Pacific coral seas was regarded as of uncertain classification, because a drawing showed a small knob of volcanic rock that emerges from it; and Rose Atoll, the small, easternmost member of the Samoan group, concerning which Couthouy was quoted as saying—apparently in error—that the "lagoon is strewed with numerous large boulders of volcanic rock," was therefore described by Darwin as "not an atoll." Both of these reefs might now be safely colored dark blue. Rotumah, north of Fiji, although now known to be adjoined by a submerged reef loop, indicating recent and rapid subsidence, was colored red, because it was reported to bear only a fringing reef: but the fringe is clearly of a new generation following the formation of the submerged reef. No records were then available for the Louisiade and Solomon groups, both of which are now known to exhibit clear indications of elevations as well as of subsidences. Moreover, although Darwin's scheme explicitly included the production of fringing reefs on shores of submergence where subsidence had been rapid enough to drown any previously formed barrier reefs, he did not identify any examples of this kind; and he therefore colored red a number of fringing reefs which can now be shown to deserve a blue tint; for example, those above noted on the west coast of Palawan and elsewhere in the Philippines and those on the well embayed granitic island of Mahe in the Seychelles group of the western Indian Ocean.

After completing his chart, Darwin remarked: "It is impossible not to be struck, first with the absence of volcanoes in the great areas of subsidence, tinted pale and dark blue . . . and, secondly, with the coincidence of the principal volcanic chains with the parts coloured red" (p. 140). "A glance at the map shows that the reefs, coloured red and blue, produced under widely different conditions, are not indiscriminately mixed together. . . . None of the large groups of reefs and islands supposed to have been produced by long continued subsidence, lie near extensive lines of coast coloured red, which are supposed to have remained stationary . . . or to have been upraised" (pp. 124, 125). He thereupon proposed a large theoretical generalization, suggested by the evidence of subsidence gained from atolls and barrier reefs, and "by the plain evidence of up-

raised marine remains" in association with fringing reefs. The generalization was that "immense surfaces [of the ocean floor] . . . have undergone a change of level either downwards or upwards during a late period" (p. 142). In this way he stepped from a simple theory of coral reefs to a broad theory of ocean-bottom deformation; but these two theories should not be confounded. Some critics have properly enough pointed out that new observations discredit the broad theory of ocean-bottom deformation by showing that the distribution of reefs and therefore the movements of the ocean bottom are more complicated than Darwin thought, for reefs of different kinds do sometimes occur in close association; but this does not in the least invalidate his simple theory of coral reefs.

There can, indeed, be little question that Darwin's map would suffer many changes if all the facts gathered since his voyage on the *Beagle* were represented upon it. With such changes his views as to the simplicity of ocean-bottom deformation would necessarily be modified; and no one would have more candidly announced the progress thus made than Darwin himself. The rising and sinking areas of the Pacific must be subdivided in a much more complicated fashion than he supposed; and even in their reduced dimensions the main movements will probably be found to be complicated by many minor movements.

A still further departure from Darwin's views is called for when it is recognized that volcanic islands may perhaps sink by their own weight, locally and isostatically, without involving broad depressions of the ocean floor, as has been suggested by Molengraaff (1916); or that they may sink somewhat in consequence of the compression of deep-lying, loosely aggregated agglomerates under the weight of later erupted materials, as Daly has proposed; or that their subsidence may be in some degree connected with a reversal of the subterranean processes that caused their eruption, as Gerland appears to have believed (1895, p. 56). Evidently enough, all these local causes of submergence may be combined in different proportions with the larger cause that is found in the deformations of the suboceanic earth crust, or with the universal cause that is found in ocean rise. It is because the chief cause of submergence, as associated with reef formation, appears to be subsidence, and because ocean rise seems, in spite of its universality when it occurs, to be of only secondary value as will be shown in later chapters, that great justification is found for Darwin's theory.

Summary

Darwin's theory of coral reefs was based on a well assured condition; namely, on the limitation imposed on reef formation by the small depth at which reef-building corals can live. Its leading postulate, island subsidence during reef upgrowth, was wholly reasonable; but the theory as the young naturalist presented it included only a few of its deducible conse-

quences. After its invention he evidently searched for other of its consequences than the manifest one of the transformation of fringing reels into barrier reefs and of barrier reefs into atolls, which the theory was invented to explain; but only three additional consequences were announced, and two of them were not confronted with the appropriate facts, because those facts were not known to him. One of these two was the great thickness that barrier and atoll reefs should possess if they have been formed by upgrowth during the deep subsidence of their foundations; the other was the internal structure that reefs thus formed should possess. A third consequence, namely, the drowning of reefs by rapid subsidence, was thought to be verified by the submerged Chagos Atoll in the Indian Ocean. Several other deducible consequences will be pointed out in the following chapter. Darwin's theory therefore did little more, apart from correlating many dissimilar facts, than explain the phenomena that it was invented to explain; but it did this so simply, so beautifully, that it was widely accepted as giving a counterpart of invisible past processes, in so far as the formation of coral reefs is concerned. That the theory was not criticized as incompletely developed is probably because the training of those who accepted it had not been especially directed to the importance of deduction and confrontation in geological theorizing.

CHAPTER III

EXTENSIONS OF DARWIN'S THEORY

Object of This Chapter

It is the object of the present chapter to set forth, in addition to the consequences of Darwin's theory which he himself perceived, a number of other consequences which he did not perceive but which have been reached by later investigators. It may well be that new consequences of the theory, at present undreamed of, will later become manifest with the further progress of earth science; and indeed one altogether unexpected consequence, a fuller statement of which will be given in Chapter XVIII, has been most ingeniously deduced and most delicately and successfully confronted with the appropriate facts on a central-Pacific atoll during the writing of this book.

Acceptance of Darwin's Theory

So convincing was Darwin's exposition of his theory of coral reefs, as presented in his careful assemblage of facts combined with his critical discussion of inferred conditions and processes, that it gained universal acceptance and held its place without a rival for some thirty years. Darwin himself was well satisfied with it, for he wrote: "With the exception of the Coral Reefs, I cannot remember a single first-formed hypothesis which had not after a time to be given up or greatly modified" (The Life and Letters of Charles Darwin (2 vols., New York, 1887), Vol. 1, p. 83). At a later date, when the theory of subsidence still had no popular rival, so eminent and competent a critic as Sir Archibald Geikie described it as one "which for simplicity and grandeur strikes every reader with astonishment. . . . No more admirable example of scientific method was ever given to the world" (1882). Yet the observations by which this admirable theory was supported were made by a young man at the age of twenty-seven on his first voyage of exploration; and his book on the origin of coral reefs, so broadly planned and so maturely executed, was published when he was thirty-three. Even today his theory of intermittent subsidence is in my opinion, especially when supplemented by Glacial changes of ocean level, more competent than any other to account for the varied phenomena dealt with; but there is another aspect of his presentation that must be mentioned. Its carefulness and impartiality have been already dwelt on. Fairness demands that its shortcomings should not be overlooked, for these are in certain respects so serious that one must frankly but regretfully question whether "no more admirable example of scientific method" than one from which certain essential elements are lacking "was ever given to the world."

Darwin's presentation was deficient in not providing independent verification for such unobservable elements of his theory as its fundamental postulate of subsidence; and this deficiency is as marked in the second edition of his book (1874), when several new kinds of verification were available, as it was in the first (1842). At that earlier time only one kind of verification was fully employed, namely that which comes from the capacity of a theory to bring many examples of the phenomena which it seeks to explain into an orderly relation not previously perceived. But this should be supplemented by some independent verification; for the essence of logical demonstration lies in showing that a given theory can explain various things that it was not invented to explain, even things that were not known to exist when the theory was invented. It is only when such verification is varied, abundant, widespread, and long maintained, that a theory concerning facts of natural science can be said to be demonstrated; and even then the demonstration is by no means absolute: it is only highly probable.

Consequences as to Facts of Distribution

Darwin was under no delusion in this matter. He was not so charmed by his theory of subsidence that he forthwith announced its truth. On the contrary, the invention of the theory, which happened, as is recorded many years afterwards in an autobiographical sketch, while he was still on the west coast of South America and before he had ever seen a true coral reef, was not mentioned under its date in his "Journal of Researches"; it was not even recorded in his manuscript journal until he had crossed the Pacific and entered the Indian Ocean. He must have gained some knowledge of coral reefs from reading at home in preparation for his voyage around the world; he was much impressed by certain geological observations in South America which led him to say that "continental elevations . . . seem to act over wide areas with a very uniform force" and therefore to suppose that "continental subsidences act in a nearly similar manner" (1840, p. 561); and he happily combined his accumulated information in a simple theory of upgrowing reefs on subsiding foundations.

Even after Keeling Atoll in the Indian Ocean had been reached, Darwin did not regard his theory as proved merely because it explained the things it was invented to explain; he proceeded to "test the truth" of it "by observing whether any uniform results can be obtained" regarding reef distribution. After a five-page summary of the facts he wrote in his "Journal": "When we consider the absence both of widely-encircling reefs and lagoon islands [atolls] in the several archipelagoes and wide areas, where there are proofs of elevations [in the form of 'raised shells and corals, together with mere skirting [fringing] reefs']; and on the other hand the converse case of the absence of such proof where reefs of those classes do occur; together with the juxtaposition of the different kinds produced by

movements of the same order, and the symmetry of the whole, I think it will be difficult (even independently of the explanation it offers of the peculiar configuration of each class) to deny a great probability to this theory" (1840, pp. 566, 567).

That admirably candid statement contains the very essence of a simple form of verification and serves to contradict those who later complained that Darwin had assumed subsidence to prove itself. He did not do so; he saw that his theory was well recommended by its capacity to explain the things that it was invented to explain, but he did not mistake this recommendation for verification. He sought and found independent verification in the facts of reef distribution. The argument that he thus employed is similar to the one that he used some years later in another connection, when he wrote in the "Origin of Species": "I believe in the doctrine of descent with modification, notwithstanding that this or that particular change of structure cannot be accounted for, because this doctrine groups together and explains . . . many general phenomena of nature" (3rd edit., 1861, p. 141).

Consequences as to Details of Structure

Darwin made a second step toward verification by deducing, as quoted above, the internal structure of a coral reef according to the requirements of the theory of intermittent subsidence; but this step was not completed, as he had no opportunity of confronting his deductions with the observed structure of elevated reefs. It is regrettable to add that a number of later observers who have had this opportunity do not seem to have taken full advantage of it, for their reports give no clear indication that they first consciously conceived the deduced consequences of various competing theories as to reef structure and then confronted them with the pertinent facts of observation. Failure to do so may have been partly because the detailed structure of elevated reefs is difficult to make out, so greatly are their outcrops obscured by calcareous incrustations and by a cover of vegetation, but partly also and perhaps largely because the significant contrasts between the unlike structures deducible from different theories were not clearly in mind.

Consequences as to Shore-Line Features

Darwin clearly recognized the need of independent verification for his fundamental postulate. He searched "for other evidence of the movements supposed by our theory," but adds that "from the nature of things, it is scarcely possible to detect any direct proofs of subsidence" (p. 147). Certain superficial changes were detected in Keeling Atoll which he took to indicate a recent small subsidence (pp. 17, 18); but this conclusion has been disputed by Ross (1855), Forbes (1879), and Guppy (1889a) with-

out, however, in the least invalidating the abundant evidences of subsidence found on the central islands of certain barrier reefs, as will be set forth below. It was left for Dana, Darwin's junior by four years to a day and his follower by a similar period in the exploration of the Pacific, to show that a subsided island ought to have an embayed shore line, when a barrier reef grows up around it, and further to point out that islands encircled by barrier reefs, as in the middle block of Figure 20, actually do have embayed shore lines. But similar results might follow from the rise

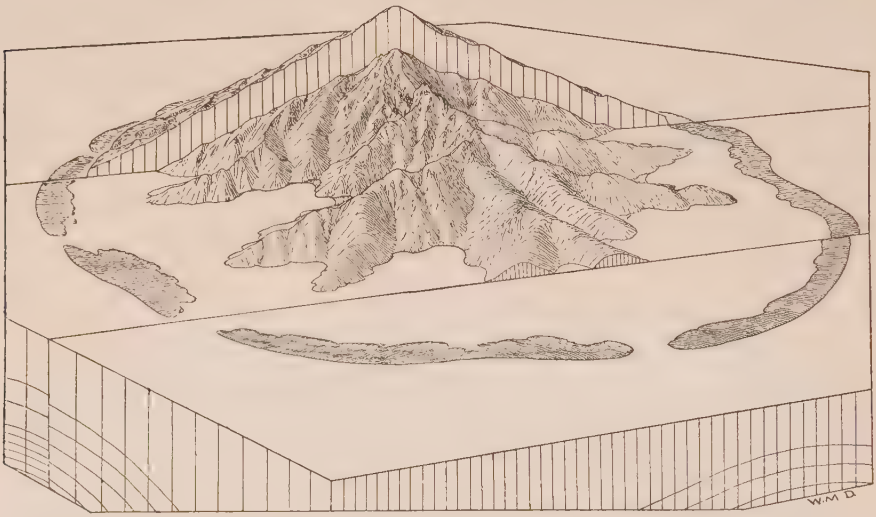


FIG. 20—Three-block diagram of a subsiding island in a still-standing ocean. A fringing reef in the background block is converted into a barrier reef in the middle block and into an atoll in the foreground block.

of the ocean around a still-standing island, as in Figure 21; and means must therefore be found of distinguishing between these two opposed possibilities.

It is difficult today to understand how a mind so keenly analytical as Darwin's could have failed to understand this phase of his problem. He knew of the occurrence of "deep arms of the sea . . . which penetrate nearly to the heart of some encircled islands"; Raiatea in the Society group (Fig. 126) was mentioned as one of them (p. 49). He saw that during the subsidence of an island "the water . . . will encroach, little by little, on the shore, the island becoming lower and smaller, and the space between the edge of the reef and the beach proportionally broader" (p. 99). Unhappily he failed to perceive also that precisely such bays as are seen in Raiatea must necessarily be produced, as shown in sectors *C*, *E*, Figure 16, if a well dissected island sinks beneath the sea.

The chief reason for this failure appears to have been Darwin's prepossession that the valleys of volcanic islands had been excavated by the sea during a supposed emergence of the islands from beneath its surface, so that their shore lines would be embayed while the islands were rising (1844,

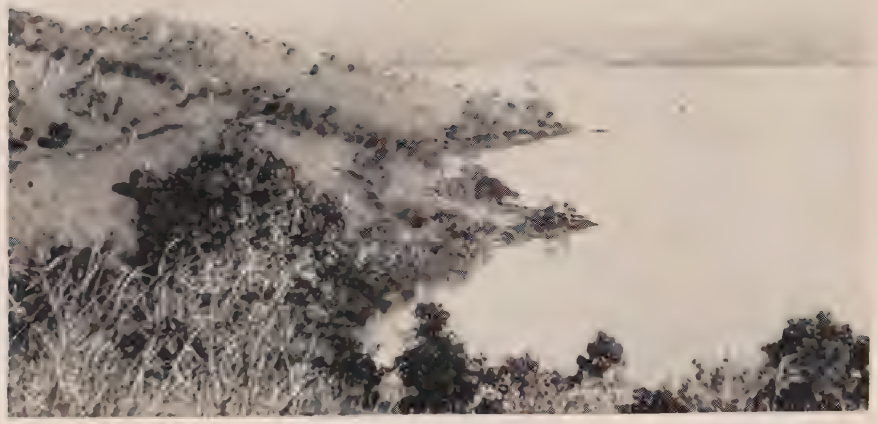


FIG. 22

FIG. 23

FIG. 22—An embayed shore line, looking southeast near northwest end of New Caledonia. (Photograph by W. M. Davis.)

FIG. 23—Outcrops of inclined volcanic agglomerates on the side of a delta-filled valley embayment, Ovalau, Fiji. (Photograph by Stinson, Suva, Fiji.)

pp. 21, 31). When Australia was reached in the voyage of the *Beagle* he did not see that the branching embayments of Port Jackson (Fig. 185) occupy submerged valleys; and on an excursion inland from Sydney to the Blue Mountains—a dissected plateau of nearly horizontal sandstones on a granitic foundation—he made explicit comparison of a valley with an emerged bay when a view was gained of an amphitheatral valley head (1840, p. 523). Curiously enough, Dana visited the same district a few years later and correctly interpreted the embayments of Port Jackson as

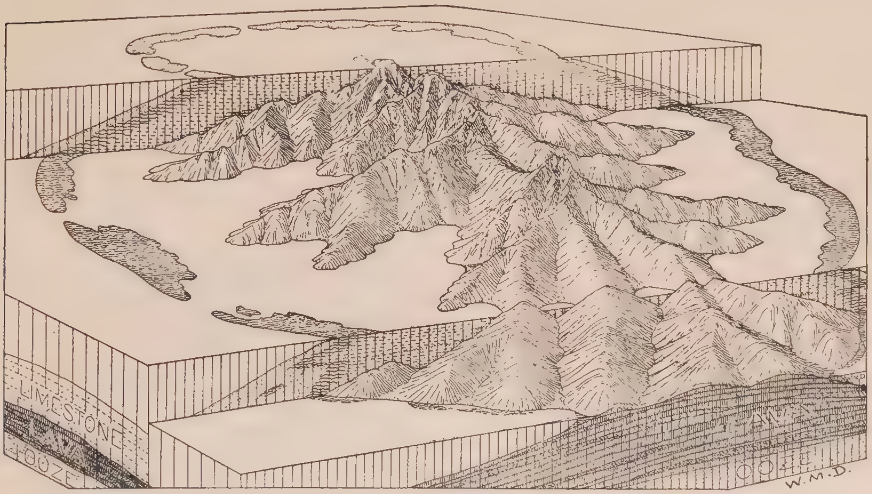


FIG. 21—Three-block diagram of a still-standing island in a rising ocean. A fringing reef in the foreground block grows up into a barrier reef in the middle block and an almost-atoll in the background block. The middle block is much the same as in Fig. 20.

the result of submergence, and the round-headed valleys in the Blue Mountains as the work of subaerial erosion (1849, p. 530). Yet Darwin appears to have understood the erosional origin of the sharp-cut valleys of Tahiti, where he was impressed by the "knife-edged ridges, having on each hand profound ravines," which had been cut after the island was formed (pp. 139, 483, 484), but he did not apply this idea to other islands; still less did he perceive that the subsidence of dissected islands would give them embayed shore lines.

DANA'S PRINCIPLE OF SHORE-LINE DEVELOPMENT

A notable discovery was therefore left for Dana, who during his Pacific voyage a few years later than Darwin's not only explained the valleys in Pacific islands by subaerial erosion (1849, pp. 379–392) but also explained, for the first time in the then slow progress of physiographic interpretation, the origin of embayments by the partial submergence of previously dissected islands (1849, pp. 131, 393). It was therefore Dana who thus, as I

have shown elsewhere in some detail (1913), gave to Darwin's theory an independent confirmation that it so greatly needed.

Like Darwin, Dana was a young man when he crossed the Pacific as a member of the United States Exploring Expedition under Captain, afterward Commodore, Wilkes. The young geologist later wrote, when recalling that early experience: "For more than five years previous to passing my third decade, I was ranging on the oceans." His first knowledge of Darwin's theory of coral reefs was gained when he reached Sydney, Australia, near the end of 1839. It was several months earlier, during the

FIG. 24—A wide bay with fringing reefs, in the

ascent of Mt. Aorai, the highest summit of the deeply dissected volcanic cone of Tahiti, that Dana first conceived the production of an embayed shore line as a necessary consequence of the subsidence of a dissected land mass. The mountain-top view of the many radial ridges and valleys of Tahiti suggested to him that: "Sunk to any level above that of five hundred feet, the erosion-made valleys of Tahiti would become deep bays, and above that of one thousand feet, fiord-like bays, with the ridges spreading in the water like spider's legs." It is curious to note that this important principle, simple as it is, had no place in geology or geography at the time of Dana's voyage. It remained for him not only to show that embayments must result from the partial submergence of a dissected land mass but also to make clear that such features cannot be produced, but must instead be as a rule destroyed, by the action of the sea (1849, p. 393). Naturally enough, therefore, "deep bay-indentations in coasts as the terminations of valleys" were mentioned as "evidence of subsidence" in his discussion of the origin of coral reefs. Figures 22, 23, 24, and 25 illustrate the clearness of this evidence.

Yet, as if to show how difficult it is at once to make full application of a new idea, Dana himself, keen observer as he was, did not perceive that Tahiti, the very island which he said would be embayed if it should subside, has actually been embayed by subsidence, but so long ago that the resulting embayments are now nearly all filled by stream-built deltas. The few that are not filled are on the southern side of the island, which Dana apparently did not visit; two bays that he mentioned on the northern side are only parts of the reef-enclosed lagoon, somewhat encroached upon by advancing delta flats. And again, as if to show how slowly a new

idea is applied to an old problem, no students of coral reefs recognized and employed Dana's principle of embayed shore lines in evidence of the subsidence of reef-encircled islands for many years after his announcement of it, not only in his famous volume on the Geology of the United States Exploring Expedition, but also in his little book, "On Coral Reefs and Islands" (1853) and in the several editions of his widely read larger book, "Corals and Coral Islands" (1872, 1874, 1890). Even Darwin himself

northwestern part of Huaheine, Society Islands.

gave little attention to Dana's principle in the second edition of his work on coral reefs (1874, pp. 163, 201); he was probably too much occupied with his studies on the origin of species after Dana's report came out to give this physiographic aspect of the coral reef problem due consideration.

Possibly the explanation of embayments by subsidence was overlooked because of the inattention of one geologist to the writings of another, regarding which Darwin wrote in 1844 or 1845 to a friend: "As for your pretending that you will read anything so dull as my pure geological descriptions, lay not such a flattering unction on my soul, for it is incredible. I have long discovered that geologists never read each other's works, and that the only object in writing a book is a proof of earnestness, and that you do not form your opinions without undergoing labour of some kind. Geology is at present very oral, and what I here say is to a great extent quite true" (Life and Letters, Vol. 1, p. 303). However, Darwin did read some books, for in 1849 he wrote to Dana regarding his report on the geology of the Wilkes Expedition: "I have not for some years been so much pleased as I have just been by reading your most able discussion of coral reefs. . . . Many of your scattered remarks on denudation have particularly interested me; but I see that you attribute less to sea and more to running water than I have been accustomed to do" (The Life of James Dwight Dana, by D. C. Gilman, New York, 1899, pp. 306, 307). Still, Darwin never applied Dana's principle of shore-line embayments to the coral reef problem as he might so well have done.

But others as well as Darwin were oblivious of this important principle. Rein and Semper, both to be referred to below as authors of new coral reef theories which they thought were better than Darwin's, apparently knew

nothing about it. The scientific staff of the *Challenger* expedition might have been expected to include at least one member who would make use of the principle; for it was declared that the selected route of that great voyage of exploration through the coral seas of the Pacific would "give an opportunity of checking and repeating previous observations on the structure of coral reefs and the growth of corals"; and the proposed geological member of the staff was advised that "at all shores visited, evidence of recent elevation or subsidence of land should be sought for, and the exact nature of these evidences carefully recorded" (1885, pp. 23, 32). Unfortunately, no geologist was included among the experts on board; and although the elaborately branching bays of Port Jackson—Sydney Harbor—in the east coast of Australia were visited, the "Narrative" of the expedition does not record the evidence for subsidence there afforded. It is only in the unofficial "Notes by a Naturalist," by Moseley, one of the zoölogical staff, that appreciative mention is made of that fine embayment: "These multi-ramified inlets . . . being in fact cañons, which by the sinking of the land have been invaded by the sea" (1892, p. 231). This is apparently the only instance in which such an origin for an embayment was recognized by a member of the *Challenger* staff.

Guppy, one of the most assiduous and painstaking students of coral reefs, apparently discredited the value of embayments as witnesses for subsidence, for he said: "I do not regard the coast configuration of an island . . . as affording, in our present state of knowledge, direct evidence of any movement whatever" (1888, p. 128). Gerland, while apparently accepting Darwin's idea of the association of subsidence and reef growth, rejected Dana's evidence of subsidence: "Ich habe lange geglaubt, der Beweis besitze auch dann keine Gültigkeit" (1895, p. 50). Gardiner took an attitude similar to Guppy's when he said that the evidence for subsidence given by embayments "when applied to volcanic islands is . . . of very doubtful value" (1898, p. 490). Yet a bay which enters a valley that is so manifestly the work of erosion as that pictured in Figure 23 from the volcanic island of Ovalau in Fiji must surely indicate submergence. Agassiz also rejected the evidence of drowned valleys, for he wrote: "There are . . . no indications that either the Marquesas or Mehetia has been subjected to the effect of subsidence, as Dana assumes" (1903a, p. 5); and he made nothing of the evidence for subsidence given by the embayments which so abundantly indent the reef-fronted coasts of the Fiji Islands or of Queensland back of the Great Barrier Reef in his detailed reports on the reefs of those regions (1898; 1899).

Among the first of modern students to recognize the importance and pertinence of Dana's principle in connection with coral reefs was Crosby, who saw during his studies of the elevated reefs of Cuba that the shoreline embayments "are the work, not of the sea, but of rivers at a time when the land was higher than now." The harbors were therefore called "half-drowned valleys" (1884, pp. 128, 120). Others are Bonney, who in

preparing the third edition of Darwin's "Coral Reefs" noted that fiord-like indentations in the rocky coasts of islands are "generally admitted to

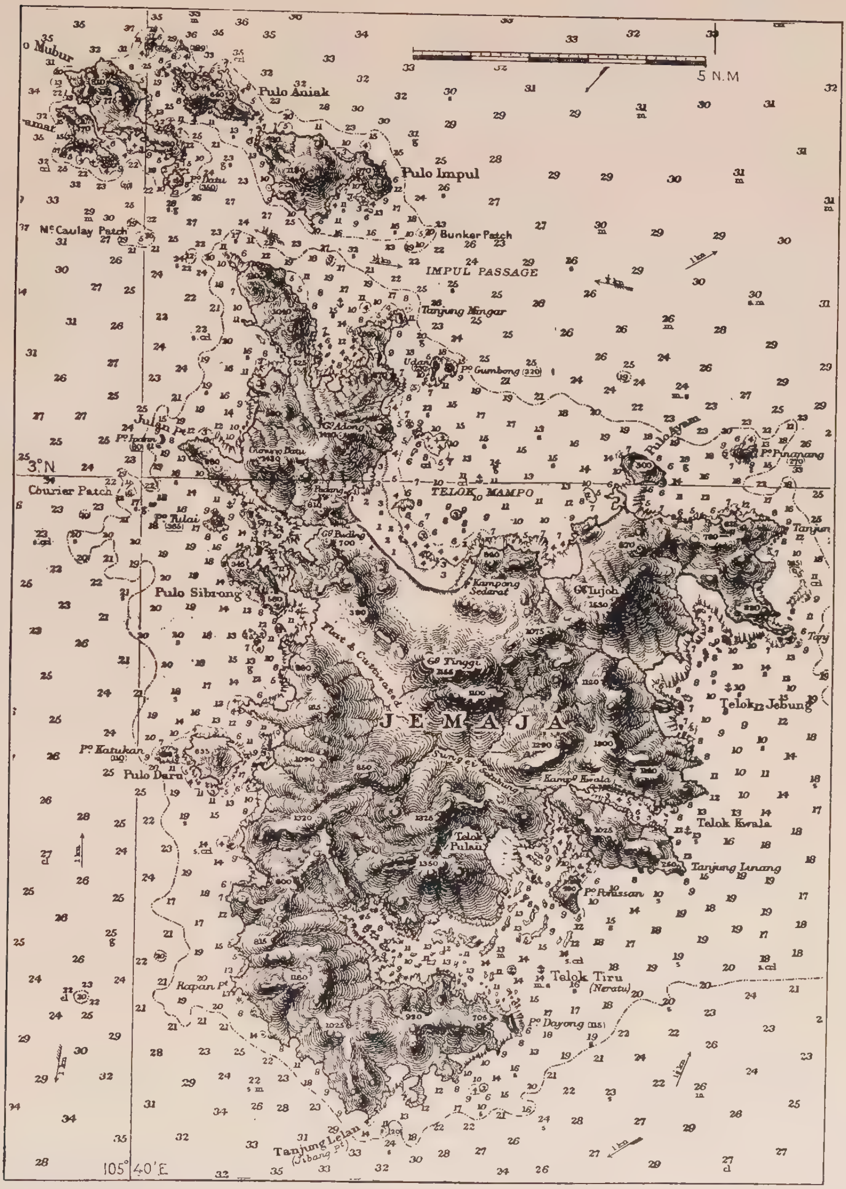


FIG. 25—The elaborately embayed island of Jemaja, Anamba Islands, in the shallow, southern part of the China Sea; HO 3038.

be one of the strongest evidences of subsidence all the world over" (1889, pp. 310, 311); Penck, who in a lecture delivered in Vienna thirty years ago

explained the embayments shown on the charts of the Queensland coast as indicating subsidence during the upgrowth of the Great Barrier Reef (1896, p. 19); Andrews, who a few years later independently used the same evidence in his excellent field study of the "New England" coast of eastern Australia (1902, p. 182; 1900–04, pp. 141, 211, 213); Hedley and Taylor in Australia, who came to the same conclusion from their observations of that coast (1907, p. 409); and Marshall of New Zealand, who has applied the principle to several mid-Pacific islands (1911, pp. 7, 13, 30).

Inequality of Submergence

Submergences or emergences of coasts and islands produced by eustatic or universal changes of sea level as a result of deformation of the sea floor or of variation of climate must affect all coasts as of the same date, rate, and amount, except in so far as their measure is affected by contemporary changes of the coasts themselves. On the other hand, submergences or emergences of coasts and islands produced by crustal movements must be of more or less unlike values and dates from region to region or from district to district, even though they may preserve a remarkable uniformity over small areas. Thus the Pelew Islands, east of the Philippines, where Semper (1880, Vol. 2, Ch. 8) described elevated reefs in the south and sea-level atolls in the north, offer a manifest example of gentle tilting, although that observer rejected such a movement as too improbable for acceptance. The westward increase of depth in the extensive banks of the Tonga group also proves gentle tilting. The Fiji group presents many examples of unequal emergences and submergences due to diverse local deformations of the sea floor thereabouts. On the other hand, there is every reason for believing that eustatic changes of sea level did actually occur during the Glacial period, when large amounts of water were withdrawn from the oceans to form continental ice sheets in the Glacial epochs and returned when the ice sheets melted in the non-Glacial epochs. It is therefore desirable to distinguish the effects of these universal changes from those due to local upheavals or subsidences. This aspect of the problem will be considered in Chapter V, on the Glacial-control theory of coral reefs.

Disappearance of Detritus

The modern understanding of the principles of land sculpture had not been reached in Darwin's time; he therefore naturally enough gave little attention to the form of reef-encircled islands. Dana, as one of those who contributed largely to that understanding, saw clearly that reef-encircled islands have, as a rule, been sufficiently eroded to transform their originally smooth, conical or domelike slopes into a succession of radial ridges and valleys. He instanced Tahiti as a typical example of a dissected cone (1886); but he gave little attention to the sequence of changes that islands suffer during that transformation or to the relation of those

changes to the development of the encircling reefs. Today no one can enter the coral reef problem successfully who does not consider that relation; for it is evident that a maturely dissected island, exhibiting radial ridge-and-valley forms such as are so generally seen within barrier reefs but possessing no wave-cut cliffs, can be explained only by supposing that a great volume of rock detritus has been removed by subaerial erosion; and the disappearance of the detritus therefore demands reasonable explanation. Rough estimates that I have made of the volume of detritus removed from certain well dissected Pacific islands in the coral seas indicate that it is from 50 to 100 times greater than that of the lagoon waters within the near-by barrier reefs and from 500 to 1000 times greater than that of the bay-head deltas now visible. A similar explanation for the relation of vanished detritus and reef upgrowth is called for in the case of the bold, deeply dissected, submountainous coast of Queensland, where it is fronted by the Great Barrier Reef of Australia.

The need of this explanation becomes all the more manifest when it is understood that fringing reefs do not flourish, indeed that they can hardly be formed at all on littoral deposits of unconsolidated detritus, such as should accumulate in the beaches and their offshore extension as sheets of shifting gravel and sand around young volcanic islands. Also, that if reefs are initiated before the littoral deposits become extensive, the active outwash of detritus from the valleys of a lofty and rainy island will soon overwhelm and smother the incipient coral growths; thereafter the undefended island will be attacked by the sea waves and cut back in cliffs, as I have shown in a special article (1916a). The disappearance of large volumes of detritus from maturely dissected islands and the development of barrier reefs around their non-cliffed but embayed shores must therefore be accounted for in some reasonable manner in any competent theory of coral reefs.

The disappearance of the detritus cannot be ascribed to its removal by wave action during an early, reef-free stage in the history of a stationary island; for, if that stage had lasted long enough to witness the mature carving of such an island, its shore would be non-embayed and strongly cliffed, and its valley mouths would be left hanging in the cliff faces well above sea level. This must be true, because the recession of shore cliffs under the vigorous attack of trade-wind surf is more rapid than the deepening of valleys by relatively short streams. Such an island would therefore be utterly unlike the embayed and non-cliffed, reef-encircled islands that are actually seen. For be it understood that the competence of open-ocean waves to cliff undefended islands and to undercut their valleys is abundantly proved by the forms of volcanic islands in the temperate zones where defending coral reefs are unknown, as will be more fully set forth in Chapter VII.

The only reasonable manner of accounting for the disappearance of the detritus that has been discharged from the valleys of a maturely dissected,

non-cliffed, well embayed and now reef-encircled island is to suppose, as I have elsewhere explained (1918c, pp. 533–537), that the island has been subsiding during the detrital discharge. It is true that the discharge of detritus probably at first prevented reef growth for a time and permitted the abrasion of cliffs; but in this case the later subsidence has been sufficient to drown completely the cliffs that were cut around the island before it was reef-protected.

Under this view of the case the larger part of the discharged detritus must be supposed to lie now at a considerable depth on the non-eroded, submarine slopes of the island; and the smaller remainder must be found in the delta and lagoon deposits that have been accumulated at rising levels during subsidence, after a lagoon was enclosed by an upgrowing reef. Manifestly necessary as this explanation is, it has hitherto had no place in the discussions of the coral reef problem. It clearly gives good reason for accepting a decidedly greater measure of island subsidence than that indicated by the inferred rock-bottom depth of valley-mouth embayments. Indeed, when an observer views a maturely dissected and well embayed island from its barrier reef and realizes the vastly greater volume of discharged detritus than of the lagoon waters, he must gain a strong impression of the evidence for subsidence thus afforded. To my regret, that impression in the presence of such an island was not included among the experiences of my Pacific voyage, for this particular verification of Darwin's theory did not occur to me until several years after my return home.

The Islets of Almost-Atolls

If a reef-encircled island stands still while reefs grow outward around it, the small islands of an almost-atoll, representing the nearly vanished residuals of a degraded volcanic cone, ought to be of low relief with very gentle slopes, as in sector *L*, Figure 28; but no such almost-atoll islets are known. If the island slowly subside during the progress of its degradation while reefs grow up around it, the form of residual islets will depend on the relation between the rates of mountain-top degradation and of island submergence. If these two causes of island disappearance be assumed to be about equal, then by the time that a volcanic cone is worn down to half height and its summits have been reduced to somewhat subdued forms though still retaining pronounced slopes, subsidence will have almost caused their submergence. Hence, under this assumption, an almost vanished island will be represented by one or several mountain-top islets, as in sector *D*, Figure 16; and such is precisely the form that almost-atoll islets possess. I have called attention to this item of verification in a special article (1920), in which a number of examples are briefly adduced; they will be cited with others in Chapter XIV of this book. The measure of subsidence indicated by the inferred rock-bottom depth of the saddles between the residual islet summits of vanishing mountain tops is a very considerable one.

The Depth of Drowned Atolls

It has already been pointed out that, if a barrier reef is drowned by rapid subsidence, it may be succeeded by a fringing reef of a later generation on the new shore line of its central island; but that, if an atoll is drowned, no new reef can be formed at a higher level. A further consequence of this contrast is that drowned atolls may be expected to lie at any depth below the surface of the sea; for, if great subsidence is accepted in the production of barrier reefs and atolls, the possible continuation of the subsidence after an atoll is drowned may lower it profoundly. Yet most drowned atolls now known lie at moderate depths, usually less than 50 fathoms, although a few banks which I believe represent drowned atolls have depths of somewhat greater measure. The absence of deeply drowned atolls therefore calls for explanation.

Two explanations may be proposed. One is that the accumulation of organic deposits on a bank compensates for its subsidence; but this is highly problematical, to say the least; for, if subsidence is sometimes rapid enough to drown a growing reef, later recurrences of such subsidence ought surely to cause a faster increase of depth than can be compensated by submarine organic deposits. The other explanation is that the absence of deeply drowned atolls is more apparent than real; for vast areas of the coral seas are still without bottom soundings. When soundings have been taken heretofore, they have seldom been carried to greater depths than 50 or 100 fathoms and "no bottom." It is possible, therefore, that when the coral seas are more thoroughly sounded, as they are destined to be by the use of the recently devised echo sounding apparatus, such a number of deeper banks will be discovered as will match the expectations of the subsidence theory. Some color of truth is given to this expectation by the recent discovery by echo sounding of the "Stewart" Bank, about five miles in diameter and about 200 fathoms in depth, in the eastern part of the China Sea where depths of 2000 fathoms prevail, as I have shown in a short article (1925) and as will be told more fully in Chapter XVII of this volume.

Unconformable Contacts of Elevated Reefs

One of the most significant consequences of Darwin's theory, easily deducible from accepted geological principles, is the unconformable contact that it necessitates between the eroded surface of the submerged foundation mass and the accumulating fringing-reef and lagoon limestones back of barrier reefs and atolls. This convincing evidence of submergence is the geological counterpart of the physiographic evidence provided by embayed shore lines. It is illustrated in the side section of sector *E*, Figure 16, and also in Figures 5 and 15, where the horizontal lagoon deposits are seen to overlap the uneven volcanic slope that was carved by subaerial erosion before it was submerged and buried. In a first-generation reef of

the kind there shown, only the reef and the exterior talus deposits may lie conformably on the never-emerged and therefore non-eroded submarine slope of a volcanic island. In the case of a reef of later generation, built after the rapid submergence of a first-generation reef, the reef and the exterior talus deposits as well as the interior lagoon deposits may have unconformable contacts with their foundation. Although contacts of this kind may sometimes be inferred for sea-level reefs, they are better exhibited in elevated reefs.

This essential consequence of the subsidence theory has been as a rule overlooked. Darwin said nothing of it, although the geological principles involved in unconformable contacts had been well worked out before his time. They were clearly stated by Hutton in 1795 (Theory of the Earth, pp. 434, 435, 449) and by Playfair (Illustrations of the Huttonian Theory, 1802, pp. 51, 52, 217 ff.). Dana was also silent on this aspect of the problem, as were nearly all the other authors so far quoted here. Thus we find yet another illustration of the prevailingly incomplete deductive analysis that has characterized the investigation of coral reefs. Yet, when the facts are appealed to, they confirm this requirement of the theory of subsidence in the most striking manner. Indeed, the capacity of this theory to explain the unconformable contact of elevated reef limestones with their eroded volcanic foundations—a fact altogether unknown when the theory was proposed—must be regarded as a verification of the theory that is as convincing as it is unexpected. Crosby, above referred to as having described the elevated reefs of Cuba in 1884, is the earliest observer I have come upon who seemed to recognize the unconformable contact of such reefs with their foundation rocks (1884, pp. 124–126). Walther a few years later published a more explicit statement of this structural relation in his account of the elevated reefs of the arid Sinai Peninsula (1888); the barrenness of the land surface there doubtless made the unconformity more manifest than it would be in the regions of abundant rainfall and dense vegetation where coral reefs usually occur.

The contact of reef limestones with their foundation can, as above intimated, be best studied after a reef is elevated above sea level; but the general nature of the contact, whether conformable or unconformable, may be in most cases safely inferred before elevation takes place. The foundation mass may consist of granites as in the Seychelles, of massive crystalline rocks and metamorphosed schists as along the east coast of Queensland, of deformed schists and sedimentary beds as along the southwest side of New Caledonia, or of volcanic rocks as in most oceanic islands. It is therefore as a rule an easy matter to show that the slanting surface of the foundation mass, where it descends beneath a fringing reef that fronts the open sea or beneath a fringing reef that follows the shore of a lagoon enclosed by a barrier reef, had suffered prolonged subaerial erosion before the reef limestones were deposited upon it. The extension of such a slanting foundation surface beneath the level of the sea means that the surface had

stood above sea level long enough to be eroded from its initial to its observed form before it was submerged; but the amount of submergence thus provable is not great, because the depth to which the unconformable contact descends below sea level is not known.

On the other hand, many elevated fringing reefs of moderate thickness are found to rest unconformably upon a hilly or submountainous slope of eroded rocks which not only passes beneath the limestones of the reefs but, continuing down the hill slope to sea level, there slants beneath sea level, as has been explained in an earlier section. Hence the amount of subsidence that either preceded or accompanied the formation of such reefs is greater than their altitude. Numerous and striking examples of this kind have been described in the Australasian archipelago, as will be duly noted on later pages. Of greater interest are certain elevated barrier reefs and atolls, the limestones of which are found to rest unconformably on a subaerially carved surface of volcanic rocks. By far the best example of an elevated barrier reef is that of Mangaia in the Cook group, admirably studied and described by Marshall; and the best example of an elevated atoll is in eastern Fiji, where it has been described with full appreciation of its significance by Foye (1918), as will be duly set forth in Chapters XV and XVI.

Biological Evidence of Subsidence

One more line of independent verification for Darwin's theory is offered by the relationships of certain forms of life that are found on Pacific islands. These forms are of a kind that appear to have had a common origin in past geological periods and a progressive separation and isolation of habitat, with resulting variations of form, in later times, such as the long-continued subsidence of a mountainous region would demand. Among the more recent writers who have discussed this problem with reference to the islands of the Pacific is Hedley, who has considered the biological relationships of Mid-Pacific islands (1899). Likewise Pilsbry (1916) and Crampton (1916) have published studies of land snails on various Pacific islands which are of great significance. But the value of this biological line of evidence is at present not fully established, because the possibility of accounting for the occurrence of animals and plants upon oceanic islands by other means—for example by transportation of embryos or seeds in hurricane winds—than as survivals of the inhabitants of confluent intermediate areas now submerged, does not seem to be completely excluded.

Objections to Darwin's Theory

Although Darwin's theory long enjoyed universal acceptance, various objections were sooner or later urged against it, the chief of which are as follows. It has been thought that the postulated instability of oceanic islands is not justified; but, as a matter of fact, instability is well war-

ranted by the occurrence of a good number of oceanic islands bearing elevated reefs as well as of a larger number of islands exhibiting the various forms that subsidence would produce. The small thickness of elevated reefs has been taken to show that the great thickness of barrier reefs and atolls, as formed by upgrowth during subsidence, is unreasonable; but the proper interpretation of the small thickness of many elevated reefs has been already shown to have no unfavorable bearing on the theory of subsidence. The absence of heavy reefs in ancient geological formations has been supposed to militate against the occurrence of heavy atoll reefs today, such as the subsidence theory demands; but, inasmuch as the heavy reefs of barriers and atolls, formed by upgrowth during subsidence, would give them a great relief over the neighboring ocean floor, it is as unreasonable to expect that such reefs should be preserved in ancient formations as that the non-eroded cones of ancient volcanic islands should be preserved there. The depths of lagoon floors and of many submarine shoals have been held to be too uniform to be accounted for by aggradation during subsidence: this matter will be fully discussed in a later chapter on the Glacial-control theory. The rarity of deeply drowned atolls in the coral seas, if it be confirmed by further exploration of the oceans, will be a more serious objection to the subsidence theory. This matter has already been briefly adverted to.

The fact that continental shores do not show the emergence that they should show, if large areas of the Pacific floor have subsided as greatly as Darwin supposed, is thought to disprove his theory of coral reefs. It is true that this fact may be taken to argue against Darwin's theory of ocean-bottom deformation; but it has already been shown that that theory should be considered apart from his theory of coral reefs. It may now be added that if the sinking of volcanic islands, to which the formation of many heavy barrier reefs and atolls is thought to be due, be explained, not as a result of a broad subsidence of the ocean bottom as Darwin inferred, but as a result of their own local subsidence by reason of their excess of weight, as Molengraaff has proposed (1916), then the shore lines of continents ought to show signs of submergence, as they commonly do, and not of emergence. For if the ocean bottom has broadly remained quiescent during the formation of numerous volcanic islands by eruption, as well as during their later isostatic subsidence, then the moderate rise of the ocean surface and the corresponding submergence of continental shores, caused by the displacement of ocean water during the submarine growth of the volcanic cones, should be maintained when the sinking cones are built up by coral reefs. Furthermore, if certain parts of the ocean floor have suffered crustal subsidence in Mesozoic and Tertiary time, as seems eminently probable in the region of the western Pacific between northeastern Australia, New Caledonia, and Fiji, where coral reefs abound, and also in the western Indian Ocean where Gondwanaland is thought to have disappeared and where reef-beset banks are now plenti-

ful, it is quite possible that some other part of the ocean floor has suffered a roughly equivalent upheaval, in consequence of the subcrustal transfer of earth material. Indeed, in view of the fact that embayments now characterize many continental coasts—apart from those regions where fiords are believed to be due to suboceanic erosion by glaciers—it would seem, quite independent of coral reef theories, that the upheaval of other parts of the ocean floor must have more than compensated the extensive subsidences of former continental areas that are believed to have taken place. Finally, it is eminently possible that the volume of the ocean has been increasing in the course of the geological ages by the addition of juvenile water set free by volcanic eruptions and hot springs; for without some such cause of ocean rise it is difficult to account for the maintenance of ocean level so little below the level of continental lowlands, in spite of great submergence of continental areas such as those above named. Such an increase of ocean volume would lessen the need of compensating for the sinking of certain ancient continental areas by an upheaval of the ocean floor elsewhere.

Summary

The foregoing pages suffice to show that the elaboration of Darwin's theory, either by the unintentional discovery or by the conscious deduction of its possible consequences, has now advanced much farther than at the time of its invention. The expansion of the theory has indeed made it a fairly complicated concept. Hence if all the various elements of such a concept are found to be correct when they are confronted with the appropriate facts, one will be warranted in saying that so successful a confrontation cannot be a matter of chance but must be a matter of merit. It will then be not because of preference or prejudice that the old theory will be accepted but because its acceptance is reasonable to a compulsory degree. Before such confrontation is undertaken, however, a number of other theories must be reviewed.

CHAPTER IV

ALTERNATIVE THEORIES OF CORAL REEFS

Object of This Chapter

However well trained an investigator may be, there is danger that, if he has but one theory for the explanation of the facts upon which he is working, he may become so fond of it as to be blind to its faults. It is therefore the part of wisdom to invent or to borrow additional theories and to show an equal and friendly attention to all of them, first by deducing for each one in its turn all its possible consequences and then by marshaling in orderly succession each group of consequences in confrontation with the facts. The present chapter attempts to do this. Each one of a number of theories, differing more or less widely from Darwin's, will be taken up in turn, and, after its adopted postulates and characteristic processes are stated, its consequences will be deduced as impartially as possible; the deduced consequences will then be confronted with the facts.

Darwin's Alternative Theories

It was not until twenty years after the appearance of Darwin's book on coral reefs in 1842 that dissenting views regarding his theory were expressed by Semper and ten years later by Rein. The views of Rein will be first presented, as they are hardly more than reflections of one of Darwin's own alternative suggestions of reef origin.

Darwin made a brief statement regarding "banks of sediment" as bases for atolls, as follows: "A conjecture will perhaps be hazarded, that the requisite bases might have been afforded by the accumulation of great banks of sediment, which owing to the action of superficial currents . . . did not quite reach the surface. . . . But . . . the assumption without any proof, that a number of immense piles of sediment have been heaped on the floor of the great Pacific and Indian Oceans, in their central parts far remote from land, and where the dark blue colour of the limpid water bespeaks its purity, cannot for one moment be admitted" (1842, p. 92; also pp. 57, 101, 198). The possible value of high submarine volcanic cones, rising to small depth in mid-ocean and thus serving as lofty bases for organic aggradation, does not appear to have been here perceived: Darwin seems to have considered only the accumulation of inorganic sediments in the formation of submarine banks. The nature and amount of organic sediment deposited on the sea floor was not known in his time.

Rein on Bermuda

Rein visited Bermuda in 1862–1863 and suggested seven years later that organic deposits, *QQ*, Figure 26, accumulated on still-standing

submarine summits, *V*, might serve as foundations for atolls, *NN*. He cited the novel results of certain dredging expeditions and added: "Was hindert uns nun, bei der Entstehung von Bermuda einen submarinen Berg oder Hügel (denn auf seine Höhe kommt dabei wenig an) anzunehmen, der . . . aus Gesteinen von hohem geologischen Alter bestehen mag und auf welchem dann als festem Halt sich ähnliche Colonien ansiedelten wie die, welche Pourtales in der Nähe der Floridariffe 90–300

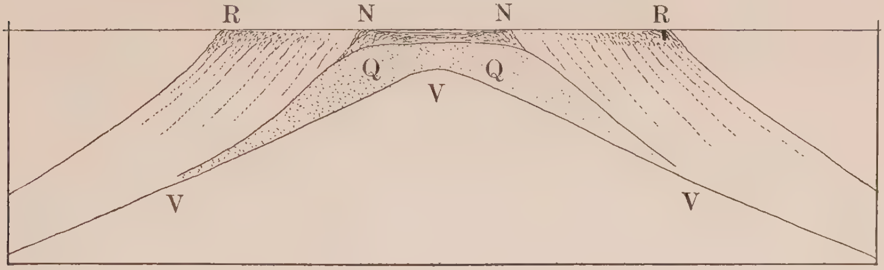


FIG 26.—Cross section of an atoll-crowned volcanic bank built on a still-standing submarine volcanic cone.

Faden tief entdeckte. . . . Als diese in grösseren Tiefe lebenden Thiergeschlechter durch fortgesetzte Tätigkeit die Unterlage, auf welcher Generationen auf Generationen Leben und Grab fand, soweit aufgebaut hatten, dass sie sich der Oberfläche des Meeres näherte, kamen endlich die grösseren Korallenbildner, setsten den Bau fort und erzeugten das Riff" (1870, p. 158).

Murray's Theory of Atolls

Ten years later still, Murray, then recently returned from his service as a member of the scientific staff of the *Challenger*, independently proposed a similar explanation for atolls, with the additional idea, previously suggested by Semper as will appear below, that atoll lagoons are enlarged by solution while the reef grows outward, *RR*, Figure 26, on its advancing talus (1880, p. 510). Shortly after the appearance of Murray's article Rein called attention to his own earlier statement and reiterated his opinion that atolls can be explained "ohne eine beträchtliche Senking annehmen zu müssen . . . denn es ist einfacher und natürlicher, dieselben als Krönung submariner Berge anzusehen" (1881, p. 46). Murray published a second article in 1888, extracts from which are given below.

There can be little question that organic deposits are formed on submarine summits; witness the dredgings on certain isolated "shoals" that rise to moderate depths in the deep ocean, as described by Buchanan (1886) and Murray (1897). If such shoals are the summits of submarine volcanoes, it is important to note that the organic deposits formed upon them must lie on a non-eroded surface, whatever inequalities of eruptive

origin that surface may have. But it is not yet known whether such deposits, if incoherent, can be built up as a bank into the surface zone of wave motion and there attain such shallowness and firmness that reef-building corals can attach themselves thereupon and grow up to the sea surface. However, if a coral reef could eventually rim such a bank, the reef as well as the bank might be built up to the surface of the sea and might thereafter increase in breadth by outgrowth at sea level.

On the other hand, it is altogether improbable that, if an atoll were built up and broadened in this way, a lagoon could be excavated in the dead limestone rock of the central area by the solvent action of the sea, as Murray assumed; for, in that case, the same solvent action ought to have prevented the upgrowth of the bank before it reached so small a depth that corals could settle upon it. This inconsistency was pointed out by Darwin in one of his latest contributions to the coral-reef problem in 1880: "It is astonishing that there should be rapid dissolution of carbonate of lime at great depths and near the surface, but not at the intermediate depths where he [Murray] places his mountain peaks" (*Nature*, Vol. 37, 1887, p. 54).

Furthermore, subsidence is excluded by both Rein and Murray on very insufficient grounds. Rein said with reference to Bermuda: "Es ist die Annahme einer Senkung um so unwahrscheinlicher, als die benachbarten Küsten von Amerika und Afrika durch Hebung trockengelegte, marine Bildungen zeigen" (1870, p. 157), a most unwarrantable conclusion. He as illogically instanced the occurrence of elevated reefs as not corresponding to Darwin's theory, although it ought to have been evident that the existence of a geological structure in an uplifted position has no bearing whatever on the conditions of its formation. Murray regarded the subsidence of volcanic islands as improbable: "Generally speaking, all the volcanic regions which we know have in the main been areas of elevation, and we would expect the same to hold good in those vast and permanent hollows of the earth which are occupied by the waters of the ocean" (1880, p. 516); but this is a very doubtful generalization, as will be shown on later pages.

Although the Rein-Murray theory of atolls was set forth with much confidence by its inventors, they offered no independent evidence of its correctness; and indeed in most cases independent evidence either in its favor or against it cannot be obtained. Its incompetence to explain almost-atolls and barrier reefs certainly militates against its acceptance. One of its tacit assumptions is not only that subsidence, as postulated by Darwin, should be rejected but that the shoaling of submarine banks by upheaval may be neglected. Yet there are only two known examples of uplifted reefs which, instead of exhibiting unconformable contacts between their limestones and their eroded foundation surface as demanded by Darwin's theory, include pelagic deposits, such as are postulated in the Rein-Murray theory, between the reef limestones and the foundation.

In both these examples the revealed structures demand, first, the depression of the eroded foundation by subsidence too rapid for reef formation, then the deposition of the pelagic deposits, and finally a shoaling by upheaval which, after pauses when reef limestones were formed at small depths, continued and raised the composite mass above sea level. One of these is Barbados, the eastward, outstanding member of the Lesser Antilles; the other is Roti in the Dutch East Indies. Both of these instructive islands contradict the Rein-Murray theory: they will be more fully described in Chapter XVI.

Acceptance of the Rein-Murray Theory

In view of the several verifications of Darwin's theory given in the preceding chapter it is certainly reasonable to consider the subsidence of atoll foundations in general as a possibility, if not a probability, and therefore to doubt the postulate of non-subsiding foundations which tacitly inheres in the Rein-Murray theory. Nevertheless various observers, uninformed as to the evidence for subsidence given by embayed shore lines, vanished detritus, and unconformable limestone contacts, have announced a "preference" for the Rein-Murray theory over the Darwin theory. Thus Forbes wrote regarding Keeling Atoll in the southern Indian Ocean, visited long previously by Darwin: "I incline to believe, therefore, that the Keeling reef foundation has arisen as Murray, Semper, and Agassiz have suggested; but that its islets have been the result of the combined action of storms and the slow elevation of the volcanically upheaved ocean floor, on which the reef is built" (1885, p. 40; also 1879). Guppy, who visited the same atoll in 1888 and published an excellent account of it, cautiously asserted that "neither of upheaval nor of subsidence is there any evidence of an unequivocal character" (1889a, p. 588); but he wrote also at about the same time: "The necessity of the explanation of [by] subsidence has disappeared, and with it the foundation of Mr. Darwin's hypothesis" (1888, p. 124). Wood-Jones, a physician who spent fifteen months on this famous atoll, also adopted the Rein-Murray theory (1910, p. 239); but his argument in its favor is based on the postulate of non-subsiding foundations, for which no sufficient warrant is found, and consists chiefly of a series of assumptions for which no sufficient proof is offered.

It is significant that apart from the outgrowth of the Keeling reef, which is an accepted factor in various theories, the three observers just quoted accept only so much of the Rein-Murray theory as pertains to invisible submarine conditions and processes and reject the relatively observable factor of lagoon excavation by solution; for all three of them agree that the lagoon is filling up. It must therefore be concluded that, in spite of the more or less complete acceptance of the Rein-Murray theory by these and other experienced observers, it still remains only an

ingenious suggestion of doubtful acceptability, in which the fundamental postulate of no subsidence is not only without direct support but is contradicted by the evidence from various elevated atolls as well as by that furnished by many sea-level and elevated fringing and barrier reefs, as will be shown in Chapters XV and XVI.

Barrier Reefs Built Up from Shallow Foundations

Le Conte in his study of Florida reefs (1857), Guppy in a description of certain reefs of the Solomon group (1884, 1884–86), Sluiter in an account of the reefs of the Java sea (1890), and Vaughan in his study of West Indian reefs (1919) have all suggested that barrier reefs might grow up from a shelving sea bottom at a considerable distance offshore. A lagoon would thus be enclosed, in the shallow shoreward part of which the water might be too impure and the bottom too muddy for coral growth.

Darwin had foreshadowed this idea in his account of Mauritius (1842, p. 52), but made little of it, presumably because it is not applicable to the steep submarine slopes of most oceanic islands or to the deep lagoons within their reefs. He applied the same view to the eastern coast of Africa, where "for a space of nearly 40 miles, from lat. 1° 15′ to 1° 45′ S., a reef fringes the shore at an average distance of rather more than one mile, and therefore at a greater distance than is usual in reefs of this [fringing] class; but as the coast-land is not lofty, and as the bottom shoals very gradually (the depth being only from 8 to 14 fathoms at a mile and a half outside the reef) its extension thus far from the land offers no difficulty" (1842, p. 56). So far as this explanation of offshore reefs is to replace Darwin's explanation of true barrier reefs, evidence should be given to exclude subsidence of the shelving sea bottom. Neither Le Conte nor Guppy nor Sluiter gave special attention to this aspect of the problem; but the detailed studies by Vaughan show that both the Recent and the Pleistocene reefs of Florida were formed when banks or platforms of earlier origin subsided (1914c, pp. 64, 65; 1919, p. 303). In the case of the Solomon Islands reefs which Guppy studied, it will be shown in Chapter XV that various changes of level, including recent subsidence, have taken place there. Most reefs of the open Pacific are not of the class here considered.

Reefs Formed on Rising Foundations

Two noted explorers, both of biological rather than of geological training, gave up Darwin's theory, which they had previously accepted, and concluded in the presence of certain facts found by them on Pacific islands that the coral reefs which they there examined had been formed around rising or emerging foundations. Semper reached this con-

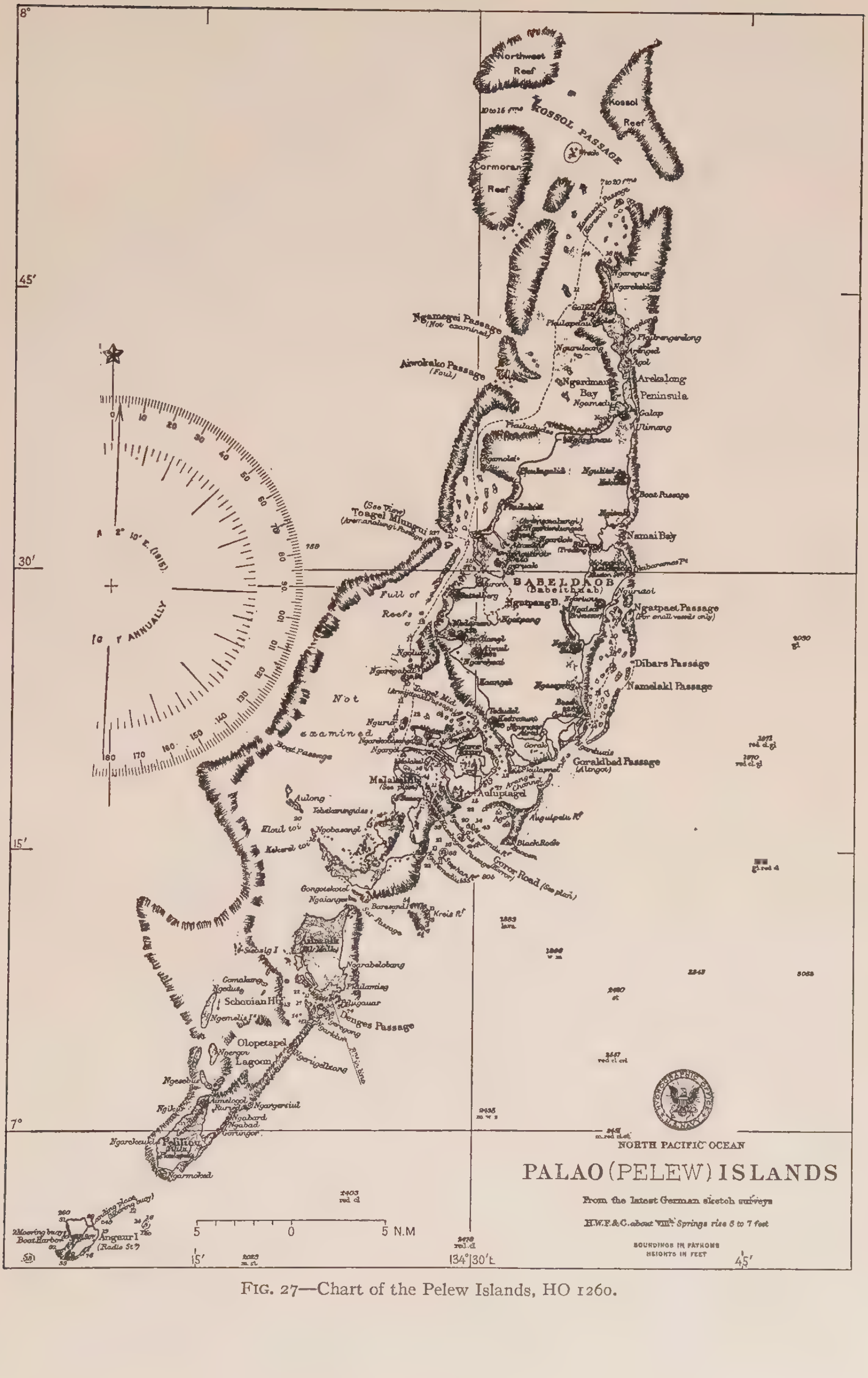


FIG. 27—Chart of the Pelew Islands, HO 1260.

clusion chiefly from his observations on the Pelew Islands, 500 miles east of the Philippines, where he spent a considerable period in 1861. Guppy reached the same conclusion independently from a prolonged examination of the Solomon Islands in 1882–1884 and was confirmed in it by exploration of Vanua Levu, the next-to-largest island in Fiji, thirteen years later.

Semper on the Reefs of the Pelew Islands

The main island, Babeltop, of the Pelew group, Figure 27, is of volcanic origin, 18 miles long north and south by 8 across and 2000 feet or more in height; it is steep-sloping to the east and more gently sloping to the west. A number of smaller islands on the south are composed of volcanic rocks, of volcanic rocks and coral limestones, or of limestones alone, some of the latter being flat-topped like raised atolls and reaching heights of 250 or 300 feet. A geological map by Otsuki (1915) shows one of these small islands to be composed of volcanic agglomerate and limestone, but it is not particularly described in his text. The little archipelago is enclosed by a sea-level reef, measuring 50 miles in north-south length by about 20 across, which borders much of the steeper eastern coast as a broad fringe with an offshore shoal and forms an outstanding barrier from 3 to 8 miles distant from the shore on the west. The enclosed lagoon is narrow and shallow near its ends and broader and probably deeper about the middle; but soundings are scanty. An independent elevated atoll forms the small island of Ngaur about 10 miles to the south; and three small sea-level atolls are distant 6, 14, and 20 miles on the north. The distance over all the islands from north to south is about 80 miles.

The first publication by Semper on these islands was a brief "Reisebericht," in which he expressed his dissent from Darwin's theory and his belief that the form of the Pelew reefs is largely determined by the movement of the sea. The fringing reef and its sloping shoal on the east seemed to him to have been held close to the coast "durch den Einfluss des beständig von Osten mächtiger Seegangs," while the corals on the west grew forward freely with a vertical face in quieter water and the lagoon was eroded or dissolved out behind them (1863, pp. 567, 568). A fuller statement was made in his book on the Philippines (1869); but his most extended account, especially concerning the Pelew reefs, is given in the seventh and eighth chapters of his work on "Die natürlichen Existenzbedingungen der Thiere" (1880, Vol. 2, pp. 39–93) and in the English translation, "Animal Life as Affected by the Natural Conditions of Existence" (1881, pp. 224–275).

Semper's views as to the Pelew Islands and their reefs are briefly as follows: The volcanic foundation, formed by submarine eruption, was slowly upheaved at a recent geological date. Channels were formed in the rising mass by marine currents; corals grew on the shoals and eventually

appeared as reefs. "The enclosed island of Babelthaup was formerly much broader than it now is" (1881, p. 270); it has been narrowed by marine erosion (p. 274); "on the western side the slope of the land is generally gentle, and small islets formed of tufa lie scattered on the surface of the inner reef" (p. 260). The elevated limestone islands south of Babeltop "are, without exception, true raised reefs [atolls], as is seen from their general form, the equal level of their summits, and the fossils found in their strata" (p. 261). "The facts here adduced suffice . . . to prove that . . . a quite recent upheaval must have occurred" (p. 263). The three small atolls on the north have been built up on rising foundations, not yet emerged, and their lagoons have been excavated by solution as the reefs grew outward. Many other statements deserve careful consideration, especially those concerned with the influence of currents on the form of coral reefs; but they are not directly pertinent to the main question here at issue.

Tests for Semper's Theory

In comment on the above extracts it may be urged that no good evidence of the submarine origin of the volcanic mass is brought forward; it perhaps represents an earlier geological philosophy in which volcanic islands were believed, as Darwin also thought, to be the product of submarine eruption followed by upheaval: if the volcanic slopes carry foraminifer-bearing tuffs, their submarine origin would be reasonable. The idea that the rising mass was channeled by sea currents—an idea which Darwin likewise held—is by no means probable. On the other hand, a number of shore-line embayments, evidently due to submergence, are shown on the chart of Babeltop and are briefly mentioned in Semper's text but without any understanding of their meaning.

Furthermore, the elevated reef limestones must, according to this theory, rest conformably on non-eroded slopes of volcanic rocks; but, unfortunately, nothing is said concerning the limestone contacts either in Semper's various writings or, with one exception, in several other accounts of the Pelew group of later date, in spite of the great significance of such contacts. The only record that Semper makes bearing on this point is: "Wichmann states, on the strength of Kubary's observations, that solid limestone lies immediately on black andesite at the southeast end of Babelthaup" (p. 260). Unfortunately, the original articles of these two earlier writers (1875, 1873) give no sufficient details concerning the contacts, the theoretical value of which was therefore presumably not recognized. The same is true of a later description of the Pelew Islands in an article by Krämer (1908), a German physician of much experience in the Pacific; his account is illustrated by a good map based on recent German surveys, in which the islands of uplifted limestone are specially marked and in which the embayed shore line of Babeltop is

clearly shown; but his text says nothing of unconformities or of embayments.

If these reef-limestone contacts are unconformable, alternations of subsidence and upheaval would be demanded. That such is really the case is highly probable because, according to Kubary (1873, p. 208), the main island has "die Gestalt von Bergketten und Thälern mit mehreren hohen Spitzen, wo der kahle Felsen hervortritt"; and this suggests that it has been much eroded after its eruptional construction and before the formation and upheavel of the little-eroded elevated reefs. Submergence is indicated not only by the occurrence of several outlying tuff islands but also by ten or fifteen larger and smaller embayments in the shore line, shown on Krämer's map as well as on a map by Friederichsen in Kubary's article. The last item was known to Darwin, who stated in the second edition of his "Coral Reefs" that Babeltop is "deeply indented with bays," but he did not infer subsidence from this fact. Perhaps it was these bays that led another writer, Wiszwianski, to reject Semper's theory and adopt Darwin's in a later general account of the islands (1909–10), although no explicit mention of embayments or of their significance is there made. More critical observations have fortunately been made recently by W. H. Hobbs, who states in a personal letter that two of the raised reefs rest on weathered and rounded lava foundations, and that in each case "the lava had been above sea level before the reef was formed during subsidence."

Semper's conception of Darwin's theory was unnecessarily rigid. He held that the association of fringing reefs, barrier reefs, and atolls in a single group militated seriously against the subsidence theory. This association may be easily explained by a gentle tilting of the group; but Semper held such a tilting to be "in the highest degree improbable" (1881, pp. 236, 255). Surely no experienced geologist would reject the evidence of gentle tilting that is offered by elevated reefs and an elevated atoll at one end of an island chain, by sea-level reefs fronting an embayed coast at the middle of the chain, and by sea-level atolls at the other end. Indeed, in view of the facts above noted, most geologists would, I believe, be inclined to regard the occurrence of such movements in the Pelews as highly probable.

In fine, Semper's unwarranted conclusion that the Pelew reefs have been formed on rising foundations and not on sinking foundations was announced in a manner that gives no indication of his acquaintance with the unlike consequences deducible from the contrasted theories under discussion; namely, conformable contacts of elevated reef limestones on their volcanic foundation and a simple shore line back of the present barrier reef, as contrasted with unconformable contacts and an embayed shore line. His text gives no intimation that he examined the islands with a conscious understanding of the meaning of these features; and yet his conclusions have been repeatedly cited in geological handbooks as if

they invalidated Darwin's theory of reef upgrowth on intermittently subsiding foundations. It would thus appear that the principles involved in the coral reef problem have been so little standardized that they are overlooked in the very books that ought to make them known.

Guppy on the Reefs of the Solomon Islands

After Guppy's return from the Pacific Ocean to England he published several essays on various aspects of the coral reef problem, as well as an important work on the Solomon Islands; and, as he had been most assiduous in observation, his writings contain many valuable records. The leading facts concerning coral reefs announced by him are briefly as follows: Several of the smaller members of the Solomon Islands, consisting chiefly of foraminiferous volcanic tuffs, are more or less encrusted with coralliferous limestones of small or moderate thickness. Some of the larger islands, which consist in great part of dense and frequently coarse-textured volcanic rocks, are benched with fringing reefs of moderate thickness at various altitudes up to 600 or 800 feet. Fringing and barrier reefs occur at present sea level; some of the barrier reefs are below sea level. A number of atolls stand not far away. In view of these facts it was held to be "self-evident . . . that these upraised reef masses, whether atoll, barrier reef, or fringing reef, were formed in a region of elevation" (1887, p. 70), the broader reefs being the result of outward growth during pauses in the elevatory movement.

This conclusion cannot be accepted on the evidence given, particularly with regard to the elevated reefs that fringe the slopes of the larger islands of dense volcanic rocks; first, because it is based on the inadmissible tacit postulate that a region which has suffered elevation has not, either before or since, suffered subsidence; and second, because the contacts of the reefs with the foundation rock are not shown to be conformable, as they should be if emergence only had taken place before and during their formation. On the other hand, Guppy's excellent descriptions, taken with large-scale charts of the islands, make it clear that the larger islands had suffered much erosion before the reefs were formed on their shores, for they have lost their initial forms of eruption; also that the eroded slopes descend below present sea level, for the shore lines are often well embayed. Hence we have here a case of the kind pointed out in an earlier chapter; namely, relatively thin, unconformable, elevated reefs which bear witness to strong subsidence before their formation, and at so rapid a rate that reef growth could not counterbalance it. Even some of the islands of foraminiferous tuff, which have evidently experienced upheaval after their encrusting reefs were formed, appear to have experienced both upheaval and subsidence before the reefs were formed; for, according to Guppy's cross sections, the reef limestones there rest unconformably on a body of gently folded and much eroded tuff beds.

Whether the limestones were deposited during the subsidence between the two upheavals or during the second upheaval remains to be proved.

As in so many other discussions of the origin of coral reefs, no sufficient consideration was here given to the means of discriminating between alternative hypotheses. Yet Guppy was certainly an open-minded inquirer, for he gave up Darwin's theory of coral reefs, which he had previously held, when he discovered facts that in his judgment invalidated it. But he nowhere made explicit statement regarding either the theoretical importance or the actual nature of the contact of a reef with its volcanic foundation, and, as already noted, he discredited without discussion the value of embayments as indicating submergence (1888, p. 128). Fortunately, he was a conscientiously careful observer, and the facts that he himself recorded compel a dissent from his opinions, as will appear more clearly when the reefs of the Solomon Islands are described in Chapter XV; but the reviewers of Guppy's book on those islands were not aware of this, as certain extracts quoted below will show. It may be added that Dr. Guppy wrote me under date of March 21, 1916, that, although he had not kept in touch with the coral reef problem for a number of years, he had come fully to recognize the force of the argument for subsidence based on drowned-valley embayments and that his antipathy to movements of subsidence had largely disappeared in the light of the evidence adduced by American botanists respecting the isolation of the floras of the Greater Antilles.

Acceptance of Guppy's Theory

A review of Guppy's work in *Nature* by H. R. Mill contains the following passages: "The theory of subsidence is so beautiful, simple, and satisfactory that very strong evidence is required to shake it, but in the history of science men have more than once been forced to say of a simple and satisfactory doctrine

. . . 'Twas beautiful,
Yet but a dream, and so—Adieu to it!'"

And he adds in closing: "Mr. Guppy has demonstrated that the old theory fails and the new succeeds in explaining the form and the structure of [the reefs in] the Solomon Islands" (*Nature*, Vol. 37, 1887, pp. 99–100). Another review of the same volume, by "W. H. H.," refers, after praising Guppy's views, to certain considerations which "may possibly help to account for the nervous reluctance of many geologists to accept any explanation of the origin of coral reefs unconnected with or adverse to the subsidence theory. . . . No matter how great may be the authority of any one individual, living or dead, if a series of facts, such as those recorded in the work before us, are plainly repugnant to the theory of subsidence in connection with the growth of reef-coral, it is the manifest duty of geologists especially to examine such facts without

prejudice, and to be ready to modify their views in accordance with the ever-advancing tide of scientific knowledge" (*Geol. Mag.*, Vol. 5, 1888, p. 171). It would here seem that the ever-advancing tide had swept the author of this homily so far forward that he lost sight of the then almost-century-long established principle of unconformable contacts and of the less long yet equally well established principle of embayed shore lines; for the application of those principles in the interpretation of the large body of facts presented by Guppy regarding the Solomon Islands reefs completely reverses the conclusions that he announced and that his reviewer accepted regarding their origin.

Murray's Theory of Barrier Reefs

Several theories of coral reefs, which have in common the explicit postulate of still-standing foundations and the tacit postulate of unchanging ocean level and which therefore exclude both subsidence as assumed by Darwin and upheaval as assumed by Semper and Guppy, differ in regard to the processes by which the form of reef-encircled islands has been modified, either before or during the growth of their encircling reefs. We may here consider those theories in an order determined first by the action of subaerial erosion in wearing down the central island; next by the joint action of subaerial erosion and marine abrasion upon it; then by the action of marine abrasion alone in cutting a bench around it; and finally by the action of abrasion in completely truncating the island.

The first of these processes was incompletely stated by Murray in association with his fuller discussion of the theory of upgrowing atolls; so incompletely indeed, that it might be passed over were it not his only explanation of barrier reefs. His chief statements are as follows: "Volcanic mountains situated in the ocean basins, and which during their formation had risen above the surface of the water, would assume a more or less sharp and pointed outline owing to the denuding action of the atmosphere and of the waves, and very extensive banks of the denuded materials would be formed around them. . . . In this way numerous foundations may have been prepared for barrier reefs and even atolls" (1880, p. 507). Even the complete obliteration of an island was thought to be possible: "All the agencies at work above the lower limit of wave action tend to wear away and level down these cones, and thus to form banks. . . . In the case of the atoll the cone may have been reduced below the level of the sea by the waves and atmospheric agencies" (1887–89, pp. 253, 257). The barrier reef of Tahiti was given as a specific example of a reef formed by outgrowth: "Everything appears to show that the reefs have commenced close to the shore and have extended seawards, first on a foundation composed of the volcanic detritus of the island, and afterwards on a talus composed of coral débris, and the shells and skeletons of surface organisms. The lagoon channel was subsequently slowly

formed by the solvent action of the sea water thrown over the reefs at each tide, and the islets in the lagoon channel are portions of the original reef still left standing. The reefs have extended outwards from the island and have been disintegrated and removed behind in the same way as the atoll has extended outwards after reaching the surface" (1880, pp. 514–515).

Tests for Murray's Theory of Outgrowing Reefs

Reefs formed by outgrowth around still-standing volcanic islands must, in their initial stage as fringing reefs, sector *G*, Figure 28, grow conform-

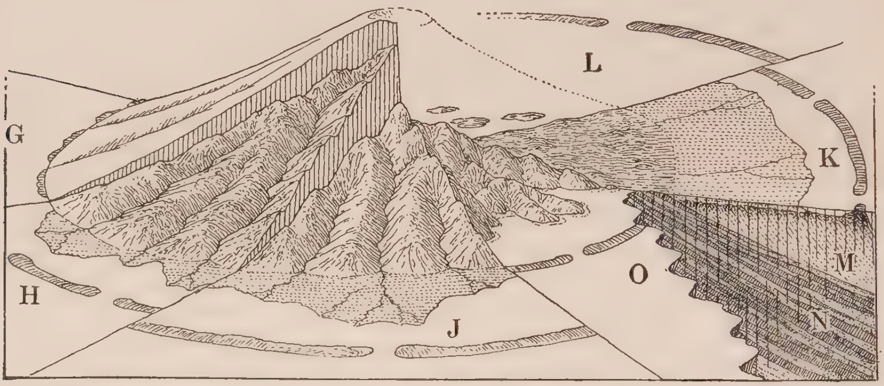


FIG. 28—Sector diagram of an outgrowing reef enclosing a dissolved-out lagoon around a still-standing volcanic island; initial stage, sector *G*; penultimate stage, sector *L*. Sector *O* illustrates the effect of island subsidence and barrier-reef upgrowth.

ably upon a non-eroded submarine volcanic slope or upon submarine deposits of volcanic detritus. The serious improbability of continued growth in presence of the abundant detritus that is washed down from the volcanic island will be shown in a later section; but this point will not be insisted upon for the present. The outgrowing reefs will consist of corals in place only to a moderate depth, representing the shallower half of the gradual slope on the exterior profile; that is the growing face of the reef. At depths greater than 40 fathoms the undermass must be composed of strongly slanting layers of coral and other calcareous detritus, which originated as a steep-pitching talus advancing into deeper and deeper water below the gradual slope in front of the growing reef. The talus layers, shown in section *M* of sector *K*, Figure 28, must as a whole have a steeper inclination than the layers of lava, *N*, which form the non-eroded submarine slope of the volcanic cone, and about the same slope as that of the slanting layers of detrital talus which may have been washed out upon the flanks of the cone before the reef was formed; but in any case the contact of the steep-pitching talus layers with the less slanting volcanic or detrital layers must not show any unconformity suggestive of either subaerial erosion or marine abrasion.

As the reef grows outward and the lagoon is excavated by solution behind it, practically all the coral in place will be removed, because the depth of lagoons is usually as great as or greater than the depth of coral growth; and only the lower part of the gentle slope and the steeper-slanting talus layers below will remain. The assumed excess of solution over deposition should leave the floor of the lagoon free from calcareous sediment and more or less cloaked with insoluble residue; and the decaying edges of the slanting talus layers should make the floor uneven, especially where it rises to the inner side of the reef; for just there solution should be incomplete although in most active progress. Inasmuch as lagoon floors are not thus characterized, their origin by solution cannot be accepted. In this connection it is profitable to consider the broad fringing reefs of the islands of Yap in the western Carolines of the North Pacific, described in Chapter XIII, and of Rodriguez in the Indian Ocean, described in Chapter XVII. These reef flats are two and three or four miles wide respectively. The long period of relative still-stand here implied, during which the reefs appear to have been broadened by outgrowth, has not witnessed the excavation of lagoons in their inner part by solution. Hence the excavation of lagoons in other still-standing and broadened reef flats is unreasonable.

The still-standing central island of a barrier reef formed by outgrowth could not have an embayed shore line, except where reëntrants are left between advancing lava flows. Valleys leading down to these shallow reëntrants would soon supply detritus to fill them with delta deposits, which would thereafter advance into the lagoon, as in sector *H*, Figure 28. Thus in time a confluent alluvial plain would be formed around the island base, as in sector *J;* the plain might eventually fill the lagoon and overwhelm the reef.

But the inner shore line of barrier-reef lagoons is always characterized, as has already been told, by numerous embayments which enter between the branching spurs of the central island, as in sector *O*, Figure 28, and which are manifestly nothing more or less than partly submerged valleys, as Dana had long before shown (1849, p. 131) and as Murray ought therefore to have known; but he never knew it. If, as Murray briefly intimated, "numerous foundations may have been prepared for barrier reefs and even atolls" by degradation, some examples of the penultimate stages of island degradation should be found, in which the original volcanic cone should be reduced to low, rolling, non-embayed hills fronted by alluvial lowlands, as in sector *K*; and occasional low isles representing the almost vanished central island should be expected, as in sector *L*, around which the lagoon waves would cut low bluffs fronted by shoals; but no such worn-down, non-embayed central islands and no such low isles are known. Atolls thus formed should have, for a time at least, a broad and shallow central area of nonsoluble volcanic rocks in their lagoon floor; but no such lagoon floors have been discovered. In no event could the lagoon lime-

stones attain a great thickness. Elevated barrier reefs and atolls should, when sufficiently dissected, disclose the various structures here deduced, although they would be concealed in sea-level reefs; but no such structures have been found.

Solution is not, as has already been shown, an active process in excavating lagoons, for their floors are as a rule covered with accumulating calcareous sediments; whatever is accomplished by solution is more than overcome by deposition. It is true that an abundant supply of sea water flows into and out of the lagoon and that great excavation might result if flowing sea water were a good solvent of limestone; but recent studies by Dole (1914, p. 75), Vaughan (1916b, p. 133), Mayor (1916), and others indicate that it is not a good solvent. Even if it were, the great volume of calcareous detritus that is washed from the reef into the lagoon might easily exceed the volume of limestone carried away in solution and thus cause aggradation by accumulation of loose sediments, such as are actually found on the lagoon floor.

Acceptance of an Inadequate Theory

If we seek to discover why none of these contradictions were noted by Murray, it will appear in the first place that he was not especially interested in the deductive extension of the postulated conditions and processes of his hypothesis to their logical consequences and in the second place that he does not seem to have been informed regarding the geologic interpretation of unconformities or the physiographic interpretation of shore lines, still less regarding the disposal of outwashed detritus from dissected volcanic islands. It was the reefs that he studied chiefly; the encircled islands received little attention; otherwise he could hardly have said: "Subsidence in past times cannot be regarded as the cause of the leading characteristics of coral reefs. There are abundant evidences of elevation in coral reef regions in recent times, but no direct evidence of subsidence. . . . It seems impossible with our present knowledge to admit that atolls or barrier reefs have ever been developed after the manner indicated by Mr. Darwin's simple and beautiful theory" (1887–89, pp. 261, 262).

Unhappily, Murray's conception of Darwin's theory was sadly incomplete, for he wrote of it: "On the subsidence theory, it is most difficult to explain the appearances and structures met with in many groups; for instance in the Fiji islands, where fringing reefs, barrier reefs, and atolls, all occur in close proximity, and where all the other evidence seems to point to elevation, or at least a long period of rest" (1880, pp. 516–517). A similar statement appears in the *Challenger* Narrative (1885, p. 508). As a matter of fact the "other evidence" points not alone to elevation or to rest but to alternating emergences and submergences of the ordinary geological kind, as will be abundantly shown when the Fiji reefs are described, especially in Chapters XV and XVI. But the most striking

testimony to the incompleteness of Murray's discussion is found in a brief article, which contains, in reference to the beautifully embayed island of Kandavu in the Fiji group, Figures 8 and 150, one of the most astonishing statements that is to be found in coral reef literature: "It was here that, not being able to apply Mr. Darwin's theory in explanation of the phenomena of the Kandavu reefs, I commenced to doubt it altogether. . . . The more observations accumulate, the more does it seem to me probable that there never was a barrier reef or atoll formed after the manner required by Mr. Darwin's theory" (1889, p. 222). In view of the importance thus given by Murray to the testimony of Kandavu against Darwin's theory, that island, which I visited in 1914, will be carefully described in the sequel, where its strong testimony for Darwin's theory will be made clear.

Earnest and convinced advocacy must count for much, since Murray's incompetent explanations have been, like Semper's and Guppy's, given favorable mention and repeatedly cited as superior to Darwin's. Nothing contributed so strongly to their acceptance as an address by Sir Archibald Geikie before the Royal Physical Society of Edinburgh in 1883, in which Murray's paper was referred to as "an important memoir, marking a totally new departure in coral-reef literature" (1883–85, p. 10); thus overlooking the facts that reef upgrowth from submarine banks had been previously suggested by Rein and that reef outgrowth with lagoon solution had been suggested by Semper. It was in this address that Geikie, neglecting Dana's principle of shore-line development even while citing from Dana's writings in which the principle is announced, declared: "No satisfactory proofs of a general subsidence have been obtained from the region of coral reefs." The address closed with the frank recantation: "In face of the evidence which has now been accumulated, I can no longer regard the accepted theory [Darwin's] as generally applicable" (1883–85, p. 27). Yet Geikie himself had, only the year before, said of that theory that "no more admirable example of scientific method was ever given to the world" (1882).

Many other essays of like tenor appeared between 1880 and 1900, rejecting Darwin's theory in favor of the views of Rein, Semper, and Murray. For example Hahn stated: "So reiht sich Thatsache an Thatsache um uns zu überzeugen, dass Darwin's Korallentheorie, an der noch vor wenigen Jahren kaum jemand zu rütteln wagte, jetzt aufgegeben werden muss. Auch unsere Lehrbücher und Leitfaden werden sich bequemen müssen, die neuere Rein-Semper'sche Theorie an der Stelle der alten treten zu lassen" (1883, pp. 190, 191). Likewise, de Lapparent, after considering Murray's theory in a review of the coral reef problem, announced: "Il ne semble pas que le phénomène corallien reclame, comme condition essentielle, une mobilité générale du lit de l'océan (1885, p. 560); and he therefore gave up Darwin's theory. Among others who have also expressed views adverse to the upgrowth of reefs on subsiding foundations are Bernard (1893), Bourne (1888), Brauer

(1896), Caullery (1900), Forbes (1885), Giraud (1902), Hickson (1890), Jordan (1882), Lehnert (1882), May (1902), Perrier (1887), Seler (1884), and Studer (1882).

Most of these authors exhibited a curiously unscientific habit of mind in rejecting a previously accepted theory because a possible alternative for it had been announced. Had they instead looked for evidence by which a logical choice could be made between Darwin's and Murray's theories, it could have been found on Tahiti and many other islands in abundance, as has already been intimated and as will be more fully shown in later chapters. The overready adoption of the alternative theory, after incomplete analysis and on insufficient evidence, as a true counterpart of external realities has been a serious hindrance to a proper understanding of the coral reef problem for forty years past. There now appears, indeed, better reason than was known at the time for the advice given, according to Huxley (1891), by Wyville Thomson, director of the *Challenger* expedition, to Murray shortly after their return to England; it was to the effect that Murray should not publish his theory, because its grounds "had not as yet been sufficiently investigated or sufficiently corroborated, and that therefore any immature, dogmatic publication of it would do less than little service either to science or to the author of the paper."

A Conspiracy of Silence

Of the many articles and reviews concerning coral reefs which appeared between 1880 and 1890 none aroused more attention than an essay entitled "A Great Lesson" by the Duke of Argyll (1887), which was reviewed in *Nature* by Bonney (1887) under the title of "A Conspiracy of Silence." It began with a most sympathetic and appreciative summary of Darwin's theory of subsidence and then continued: "And now comes the great lesson. After an interval of more than five-and-thirty years the voyage of the 'Beagle' has been followed by the voyage of the 'Challenger,' furnished with all the newest appliances of science, and manned by a scientific staff more than competent to turn them to the best account. [The absence of a geologist was thus overlooked.] And what is one of the many results? . . . It is that Darwin's theory is a dream. It is not only unsound, but it is in many respects directly the reverse of truth: With all his conscientiousness, with all his caution, with all his powers of observation, Darwin in this matter fell into errors as profound as the abysses of the Pacific. All the acclamations with which it was received were as the shouts of an ignorant mob. . . . The overthrow of Darwin's speculation is only beginning to be known. It has been whispered for some time. The cherished dogma has been dropping very slowly out of sight. Can it be possible that Darwin was wrong? Must we indeed give up all that we have been accepting and teaching for more than a generation? Reluctantly, almost sulkily, and with a

grudging silence as far as public discussion is concerned, the ugly possibility has been contemplated as too disagreeable to be much talked about." And on a later page it was said that "Mr. Murray's new explanation of the structure and origin of coral reefs and islands was . . . supported with such a weight of facts and such a close text of reasoning that no serious reply has ever been attempted." Guppy's views also were referred to with approval (1887, pp. 301, 305).

Bonney's review above noted refuted the charge of grudging silence and referred especially to Dana's adverse criticism of Murray's views (1885); and Huxley caustically pointed out certain "new misrepresentations" that were "evolved out of the inexhaustible inaccuracy of his Grace's imagination" (1887; also 1888, 1891). It is therefore unnecessary to add more here about the abysmal depth of Darwin's error or the shouting ignorance of the mob which had for a generation acclaimed his error as truth. The curious incompleteness of the arguments on both sides of the discussion should, however, be pointed out; for during its whole course there was no satisfactorily clear analysis of the postulates, no critical deduction of the consequences of the competing theories, no thoroughgoing confrontation of deduced consequences with pertinent facts. Hence there was no sufficiently objective ground discovered for an impartial decision as to the merits of the theories under examination, although among those who took part in the discussion were Geikie, Murray, Huxley, Bonney, Guppy, Judd, and others well known in the geological circles of the time. The "great lesson" of the occasion is therefore really not the supposed overthrow of Darwin's theory but the danger of incomplete discussion. When the history of nineteenth-century science is written, the coral reef chapter will not be in all respects flattering to the acumen of many who contributed to it.

Agassiz' Theory of Submarine Platforms

The first extract from Murray's writings in the preceding chapter contained mention of the denuding action of the waves as well as of subaerial agencies, but no specific consideration was given to their work. The joint action of the two denuding processes in the production of littoral platforms around still-standing islands will now be examined as part of a scheme of barrier-reef and atoll formation announced by several other authors.

Alexander Agassiz, the most experienced modern explorer of coral reefs, after making an elaborate examination of the islands and reefs of Fiji, believed that "the submarine platforms upon which the barrier reefs" of that group have grown are "merely the flats left by the denudation and erosion of the central island." The barrier reefs of Fiji "have not been built (as is claimed by Dana and Darwin) by the subsidence of the islands they enclose. They are not situated in an area of subsidence, but on the

contrary in an area of elevation" (1899, p. 135). He continued: "All the evidence to be gathered in Fiji tends to prove that preceding the present epoch there was an extensive elevation. . . . It is to the changes brought about by the elevation and the subsequent erosion and denudation that we must look for the causes which have fashioned the steep slopes of the islands and reefs" (pp. 133, 134). "In all the cases I have examined, the reefs form but a thin crust on the underlying base" (p. 144). Confident mention is made of the "platforms of submarine erosion upon which the barrier reefs have grown" (p. 135) as forming "characteristic features of the islands of Fiji" (p. 136); thus implying that the platforms had been eroded before the reefs grew upon them; and it is concluded that the corals "have found a footing upon the flats due to submarine erosion and to denudation and to the action of the atmosphere and of the sea" (p. 138; also pp. 130, 136).

My own observations in Fiji led me to altogether different conclusions. It may be noted at once that the region is not one of mere elevation but of diverse and successive movements, varying in sign, date, area, rate, and amount. If platforms of submarine erosion occur, they are exceptional; most of the reefs are not thin crusts but heavy structures; and their formation has repeatedly taken place by upgrowth during the slow subsidence of their foundations, of whatever shape, essentially as Darwin and Dana believed. Definite grounds for these statements will be presented in later chapters.

Agassiz had previously expressed a similar opinion to that above quoted for Fiji about the lagoon of the Great Barrier Reef of Australia, the present condition of which he thought could "be satisfactorily explained by the mere action of erosion and denudation, which has been going on for so long a time along the coast of Queensland. It is undoubtedly the same erosion and denudation which have separated Northern Queensland from New Guinea" (1898, p. 127)—a separation which most geologists attribute to subsidence. "The farther east the more and the longer has the shore line been exposed to the disintegrating action of the sea. Thus the outer islands and islets first separated from the coast were reduced to the level of the sea long before the inner islands now forming the various archipelagos along the eastern coast of Queensland and within the Barrier Reef were separated from the mainland. On the flats thus formed, and on their outer edges, corals began to grow, and as the process of disintegration and erosion extended inland the corals followed in the same direction" (p. 126). My own sight of the Queensland coast in 1914, interpreted in the light of Andrews' excellent physiographic studies there (1903, 1900–04), led me to a very different conclusion in which subsidence plays a leading part (1917b), as will be here told in Chapter XIII.

Agassiz again wrote of a rock platform bearing superposed reefs in his account of Tahiti, which he visited during a long voyage across the tropical Pacific (1903a, pp. 141–156). He explicitly stated that "the

northeast trades have eroded a wide platform on the east side of Tahiti," on which "here and there an outlier of the volcanic rock can still be traced, giving us a clue to the nature of the underlying platform, and plainly showing that it is only the extension of the spurs of the mainland which have been eroded and washed out to sea" (pp. 149-150); and again that "the wide platform carrying the fringing and barrier reefs of the west side of Tahiti has been formed by submarine erosion" (p.146). It would therefore appear from these passages and from others of similar tenor, especially from such phrases as "platforms of submarine erosion upon which the barrier reefs have grown," that Agassiz believed that the "underlying base" had been prepared by the sea before the "thin crust" of coral reefs was built upon it; but, if so, the base must have been a rock platform of marine abrasion cut on an unprotected shore, and as such the platform should have been backed by strong cliffs rising around the non-subsided and therefore non-embayed coast. This interpretation of his views has, however, been objected to (*Science*, Vol. 43, 1916, p. 894). He must therefore have meant that the "denudation and erosion" of the islands has been accomplished, even to the excavation of the lagoons with depths of 30 and 40 fathoms and of the bays that indent the shore, after protecting reefs had been established on the original shore line; but that seems as impossible as the exclusion of subsidence from all share in lagoon and bay production seems unreasonable. There are, however, a few passages which appear to bear out this extraordinary view. For example, the lagoon floors of certain atolls are declared to be, like those of barrier reefs, "flats from the surface of which the islands have at first disappeared and the interior parts of which have next been removed by the incessant scouring of the action of the sea, the ceaseless rollers pouring a huge mass of water into the lagoon, which finds its way out of the passages leading into it or over the low outer edges of the lagoon" (1899, p. 135). "The water becomes charged with particles of lime or of other material, and we soon have all the elements of a modified gigantic pothole, from which the churned material is carried out by the currents flowing through the entrances into the lagoon" (p. 139). "There seems to be no question that the action of the sea can cut out the lagoons of barrier reefs and of atolls at the depths at which they have been observed in the Fijis" (p. 140).

Objections to Agassiz' Views

Had any observer of less experience than Agassiz set forth this explanation it would seem hardly worth controverting; but, in view of his eminence as a student of coral reefs, several reasons for dissenting from it must be stated. They are as follows: First, the overwash of sea water is not an effective excavating agent back of a fringing reef; so long as the reef is narrow and close to the shore the surf may cut low bluffs in spur ends; but the rock platform in front of the bluffs is always shallow. Sec-

ond, where a narrow barrier-reef lagoon exists, the current through it is a less efficient destructive agency than its surface waves, witness the shallow rock platforms back of its spur-end fringing reefs in contrast to the presence of fine sediments and not bare rock on the lagoon floor, to say nothing of the fringing reef itself by which the destruction of the submarine prolongation of the spurs is so effectually prevented. Third, although it is not to be denied for a moment that great volumes of sea water surge over a barrier reef and thus enter its lagoon, from which they must find exit chiefly by passes or breaches, the comparison of the lagoon to a gigantic pothole is not warranted, because in a pothole the eddying current of the water is often faster than the general flow of the stream, while in the relatively deep lagoon the drift of the water is much slower than the shallow, surf-impelled current which flows over the reef flat. Yet even that current usually acts constructively, for it carries the supply of reef detritus, received from the breakers on the exterior or growing face of the reef, across the flat and deposits it for the most part on the slope where the flat slants down into the lagoon.

Fourth, the embayments of the island shore lines in Fiji, to which Agassiz made only brief and unappreciative references (1899, pp. 136, 143), are even less producible by lagoon currents and coastal streams than the lagoon itself. Such embayments are manifestly not now in process of excavation but are in process of obliteration by delta deposits. Fifth, the very existence of a shallow rock platform of submarine erosion —like the small thickness of the reefs that are believed to rest upon it— must be questioned. The platforms are by no means sufficiently established by observation, in spite of the definiteness with which they are described. In examples of uplifted reefs to be presented in Chapters XV and XVI evidence will be given that excludes the existence of platforms. And, even if a platform could be produced by submarine erosion in the manner described, it would still be necessary to demonstrate that shore-line embayments could be and actually had been produced by that process and not by the very simple alternative process of subsidence, which is a much more manifest possibility. Furthermore, the upheaval of some of the Fiji Islands, as proved by their elevated reef limestones, does not exclude the contemporary subsidence of other islands, nor the earlier subsidence of those same islands. Similarly, the initiation of subsidence along the Queensland coast in Cretaceous time, which Agassiz recognized, does not exclude the continuation of subsidence, more or less intermittently, through the long stretches of Tertiary and Quaternary time; yet he denied this later subsidence.

As none of these alternative possibilities receives adequate consideration in Agassiz' reports, his views as to the origin of lagoons and as to the small thickness of sea-level barrier and atoll reefs cannot hold higher rank than preferred but unverified suggestions. In spite of the emphasis with which the small thickness of sea-level reefs is often asserted, it is

not shown to be a fact of observation. It is an inference, and the inference is based on a faulty scheme of lagoon excavation and reef development. Agassiz' descriptions of reefs and lagoons are unrivaled, but the accounts that he has given of reef-encircled islands are incomplete: they do not indicate an understanding of physiographic principles. It is largely for that reason that his conclusions cannot command acceptance. It may be added that Agassiz' scheme of widespread elevation in the Pacific (1899, p. 135) appears to be as far from the truth as Darwin's scheme of widespread subsidence; but, while Darwin's theory of reef formation appears to hold good, Agassiz' theory of reef formations does not.

Veneering Reefs on Wave-Cut Platforms

Tyerman and Bennet on the Society Islands

The action of waves alone in cutting a platform or bench around oceanic islands in the coral seas may now be further examined in connection with a very explicit theory of abrasion that was first announced even before Darwin's time by Tyerman and Bennet, members of the London Missionary Society traveling in the Pacific, who wrote pleasingly and teleologically of the Society Islands, apparently with special reference to the island of Tahiti, the only member of the group that is rimmed with cliffs, as follows:

Before the reefs "had attained sufficient extent and elevation the tide must have had full access to the foot of the mountains; and the many high cliffs which rise abruptly . . . seem to indicate that the islands themselves were once much larger than they now are; and, consequently, that the sea has removed all the ground which lay between the present steep faces of the mountains and their original boundary. . . . As the reefs grew beneath the flood, the force of the ocean against the land would be gradually diminished; and, when the former reached the surface of the water, they would afford (as they do now) protection to the shore from all further encroachment on the part of the tide. . . . Under the direction of a wise and beneficent Providence, how much are these islands indebted to the poor and slender coral insect, for the construction of those mighty moles that curb the fury of the mightier deep, and, by their happy interference, have occasioned those fruitful lines of level soil to spread between the hills and floods, which furnish the inhabitants with the principal part both of their food and raiment!" (1832, Vol. 1, pp. 215, 216).

The island of Tahiti, which is truly for the most part rimmed with cliffs from the submerged base of which a platform of abrasion must extend seaward, gives some support to this view; but the other members of the Society group, in which sea cliffs are almost or quite wanting, contradict it. Even for Tahiti no sufficient explanation is offered for the depth

of the abraded platform, now buried under lagoon deposits, or for the delta-filled embayments by which the cliffs are repeatedly interrupted, or for the change from abrasion to reef growth. All these features will be accounted for in Chapter XIII by subsidence after the cliffs were cut.

Darwin mentioned Tyerman and Bennet's suggestion and commented on it as follows: "It will, perhaps, occur to some, that the actual reefs formed of coral are not of great thickness, but that before their first growth, the coasts of these encircled islands were deeply eaten into, and a broad but shallow submarine ledge thus left, on the edge of which the coral grew; but if this had been the case, the shore would have been invariably bounded by lofty cliffs, and not have sloped down to the lagoon-channel, as it does in many instances. On this view, moreover, the cause of the reef springing up at such a great distance from the land, leaving a deep and broad moat within, remains altogether unexplained" (1842, pp. 48, 49). This passage shows that Darwin had a clear understanding of the essential association of rock platforms and sea cliffs, and also that he correctly generalized the forms of most reef-encircled volcanic islands as not being cliffed; but it also shows that he, like Dana and most other visitors to Tahiti, did not recognize its sea cliffs as such. Agassiz is one of the very few observers who has given an appreciative account of them, although even he did not recognize that they have been partly submerged since they were cut back.

Guppy on Wave-Cut Platforms

The reasons just quoted from Darwin for rejecting the theory of veneering reefs are so sufficient that it would not deserve further mention, had it not been revived half a century later by Guppy, who gave it unqualified adherence. He wrote: "I will pass over the theory of subsidence . . . because the more recent facts concerning the ocean depths and the regions of living and upraised reefs compel us to regard it as no longer necessary" (1890, p. 51). Then, after discussing the work of the waves and currents in preparing a platform for the growth of barrier reefs, he concluded: "The more gradual the land-slope, the broader will be the submarine ledge [platform], cut out in the course of ages by the action of the sea, and the more distant will be the barrier reef that has grown up along its margin. This I believe to be the true explanation of the position of barrier-reefs" (1890, p. 61).

It would surely have been more reasonable to search for impartial tests by which an objective choice could be made between the rival theories of subsidence and of abraded platforms, before rejecting one as "no longer necessary" and adopting the other one as "the true explanation"; and it would seem to be essential that some efficient cause should be indicated by which reef-building corals should be excluded from an island border while abrasion is in progress and permitted to establish themselves upon it after a certain amount of abrasion has been accomplished; but no attention was paid to either of these vital matters.

Tests for the Platform Theory

Fortunately, tests for Guppy's still-stand theory in contrast to Darwin's subsidence theory may be easily provided by deducing the essential consequences of each theory in so far as they concern the shore-line features that should be seen on an encircled island after a barrier reef has grown up and enclosed its lagoon. Thus, according to Guppy's state-

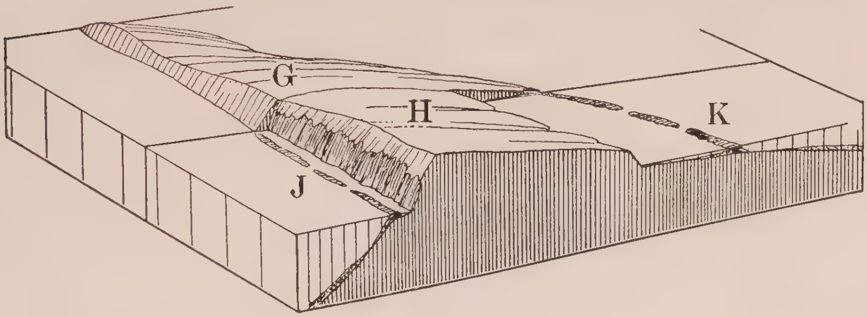


FIG. 29—Block diagram to illustrate the effects of abrasion and reef growth on a still-standing island of unsymmetrical slopes.

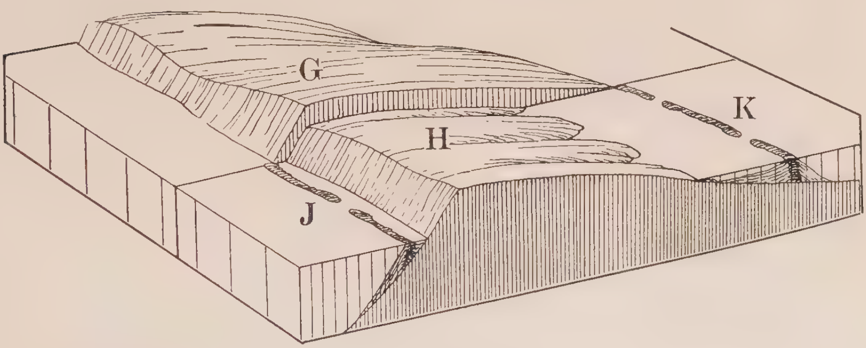


FIG. 30—Block diagram to illustrate the effects of subsidence and reef growth on a similar island.

ment, a still-standing island of unsymmetrical slopes, as shown at *G* in the background of Figure 29, will have a narrow platform cut on its steeper side and a broader platform cut on its more gently sloping side; and the reefs afterwards built up on the platform margins as in the foreground, *H*, of the Figure, will be near the shore, *J*, and distant from it, *K*. But the same disposition of reefs will obtain if an unsymmetrical island, *G*, in the background of Figure 30, subside, as in the foreground, *H*, while reefs, *J*, *K*, grow up from its former shore line. Hence the situation of the reefs does not give basis for a choice between the two theories. But the first theory demands that the island shore lines shall be cliffed and not embayed; the second, that they shall be embayed and not cliffed. A more crucial test can hardly be imagined. When it is applied, no doubt whatever can remain as to the choice to be made: for practically all

islands encircled by barrier reefs have embayed, non-cliffed shore lines. The several sectors, *H*, *J*, *K*, of Figure 31, give further illustration of the consequences of abrasion arbitrarily followed by reef growth around a still-standing island; the low cliffs of sector *H* being associated with a near-by reef, the stronger cliffs of sector *J* with well offset reefs, and the almost consumed island of sector *K* with a distant reef. In the first two cases, deltas below hanging valleys should advance into the lagoon, as in

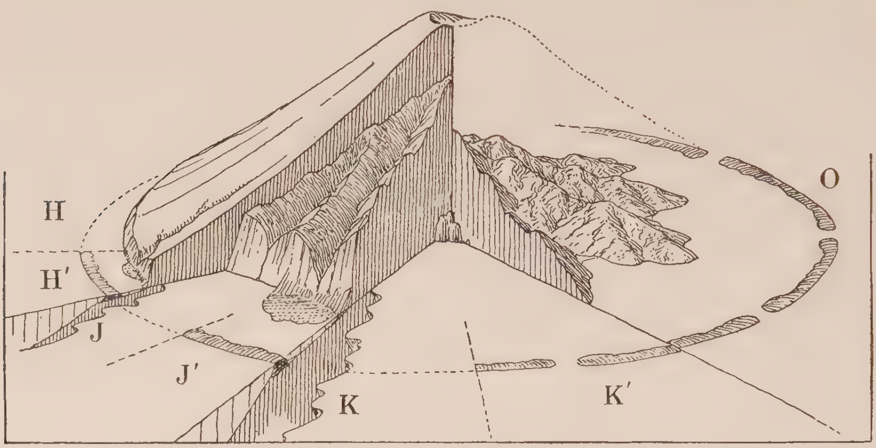


FIG. 31—Sector diagram to illustrate, sectors *H*, *J*, *K*, the relation of abrasion and reef growth on a still-standing island. Sector *O* shows the effect of subsidence and barrier-reef upgrowth on a non-abraded subsiding island.

sectors *H′* and *J′*. No reef-encircled island in the coral seas, with the possible exception of Tahiti, exhibits this association of forms. Nearly all reef-encircled islands have sloping, non-cliffed spurs between drowned-valley embayments, as in sector *O*.

It should not be overlooked, however, that examples of oceanic islands with cliffed shores are well known. Such is the prevalent form of islands in the cooler seas where coral reefs are not present to protect them from the waves. Witness St. Helena, of which Darwin long ago wrote: "The enormous cliffs, in many parts between 1000 and 2000 feet in height, with which this prison-like island is surrounded, with the exception of only a few places, where narrow valleys descend to the coast, is the most striking feature in its scenery" (1844, p. 91). Witness also Tristan da Cunha, here shown in Figure 64, reproduced from a view in the *Challenger* Narrative (1885, p. 241); it is rimmed around with high cliffs, down which streams cascade to the beach and into which no bays enter. The only similarly cliffed and non-embayed island in the warmer oceans is Réunion in the western Indian Ocean; its reefless coast will be described and explained in Chapter X. Several other cliffed islands are known in the coral seas, but they all have embayed shore lines, as if they had been somewhat submerged after being cliffed, as will be told in Chapter XI.

In strong contrast to cliffed islands, the central islands of nearly all barrier reefs are not cliff-rimmed around a simple shore line but are embayed around a non-cliffed shore line, evidently because their encircling reefs have protected them from wave attack during their embaying submergence. Furthermore, if sea-level barrier reefs are built up from abraded platforms of moderate depth, then uplifted barrier reefs should, when sufficiently dissected, reveal a flat platform cut in volcanic rocks beneath their limestones; but it may be said at once that, as far as the contact of uplifted reefs with their foundation has been observed, it is a sloping surface such as the theory of subsidence demands, as will be told in Chapter XV. The only exceptions to this statement that I have found are a few small reefs described by Hill in an account of Jamaica (1899, p. 100).

It is not easy to understand how Guppy's belief was guided when he revived the theory of veneering reefs and unwarrantably decided in its favor. The method of crucial tests is nothing new. The consequences of the two theories as above presented are easily deduced, and the confirmation of the correctness or incorrectness of the deductions by confronting them with facts of observation is easily accomplished. Such confrontation may be made by a voyage in the coral seas or, more easily, by an examination of the many excellent, large-scale hydrographic charts of Pacific islands, now generally accessible. The confrontation is immediately and overwhelmingly in favor of one theory and against the other. It is surely not asking too much that this reasonable procedure should be followed before a "belief" in any theory is announced. Indeed, one might fairly expect that those who took part in the discussion which followed Guppy's address on the coral reef problem in London in 1890 should have at least intimated the need of some such procedure; but such was not the case. Some of his hearers expressed a qualified dissent from certain of his conclusions, but none of them seem to have regarded subsidence as playing any part in reef formation; none of them asked for an impartial test of his views.

Wharton's Theory of Marine Abrasion

An interesting extension of the theory of veneering barrier reefs to the case of atolls has been advocated by Wharton, who as a British naval officer had had much experience in hydrographic surveys in the Pacific. He said: "It is very remarkable that no matter how vast the lagoon, and how deep the steep outer slopes, no lagoon has more than a certain depth, and that such a limited depth that isolated coral heads can spring out of it; and I cannot make this general fact fit with a general theory of subsidence, even when varied by occasional elevations" (1890, p. 172). Returning to the subject a few years later, he wrote: "When we examine banks in the open sea, we find . . . that there are a great many with a

general depth of from 30 to 40 fathoms, and the question arises whether this may not be the general limit of the power of oceanic waves to cut down the mass acted upon when it is fairly friable" (1894, p. 709).

At a still later date Wharton stated, again tacitly postulating still-standing islands, that the effect of waves driven by strong winds in a deep ocean "will be to cut down an island more or less rapidly, according to its constitution, to a very considerable depth below the surface, the final result being a perfectly flat bank" 30 or 40 fathoms deep, around the rim of which reefs might subsequently grow up to the sea surface; and he then ascribed the flatness of lagoon floors and their fairly uniform depth to "the cutting down of volcanic islands by the action of the sea" (1897, p. 392). Indeed, he ascribed to this operation not only the flat floors of ordinary banks and atolls, but even the vast Seychelles bank in the Indian Ocean, which measures about 200 by 80 miles, with a general depth of 30 or more fathoms.

Wharton thus gave desirable emphasis to a very striking feature of reef-enclosed lagoons, namely, their small range of depth; but his theoretical views are not acceptable. In the first place, he misapprehended the meaning of the phrase "deeply concave surface" in Darwin's book (1842, p. 93); for, although it is there used to describe the form of an atoll-lagoon floor, which is also said to be a "saucer-shaped hollow" (p. 28) and of "bason-like form" (p. 93), the saucer or basin must be understood to have a broad, flat bottom; for another passage in Darwin's book states explicitly that "the greater part of the bottom in most lagoons is formed of sediment; large spaces have exactly the same depth" (p. 26). In the second place, Wharton tacitly assumed that, previous to their truncation, volcanic islands are not defended by growing reefs, for otherwise they cannot be truncated; and he then made the further assumption, but without advancing any reasons in support of it, that, not until after truncation is completed, will reef growth begin.

In the third place, the possibility of a volcanic island being reduced to a "perfectly flat," 30- or 40-fathom bank by normal abrasion is very doubtful, unless an eternity of time is allowed for the task, during all of which the island suffering abrasion must remain stationary. For, although the truncation of a volcanic island to a bank of small depth might be accomplished relatively soon in the geological sense of that word, the further wearing down of such a bank to a depth of 30 or 40 fathoms would demand an excessively long time. The time would be reduced if the island were composed of "fairly friable" material, as Wharton first assumed; but the deeper central mass of a volcanic island may have no such constitution: witness the very resistant core of Tahiti. Again, the depth of 30 or 40 fathoms might be given to a shallow bank by subsidence; but if that factor be allowed to enter, the small range of lagoon depths becomes again as much of a problem as ever; and besides, subsidence held no essential place in Wharton's theory. He contended that "without

subsidence, deep and large atolls may be formed, and . . . we have abundant evidence of atolls so forming. I am not arguing that there has been

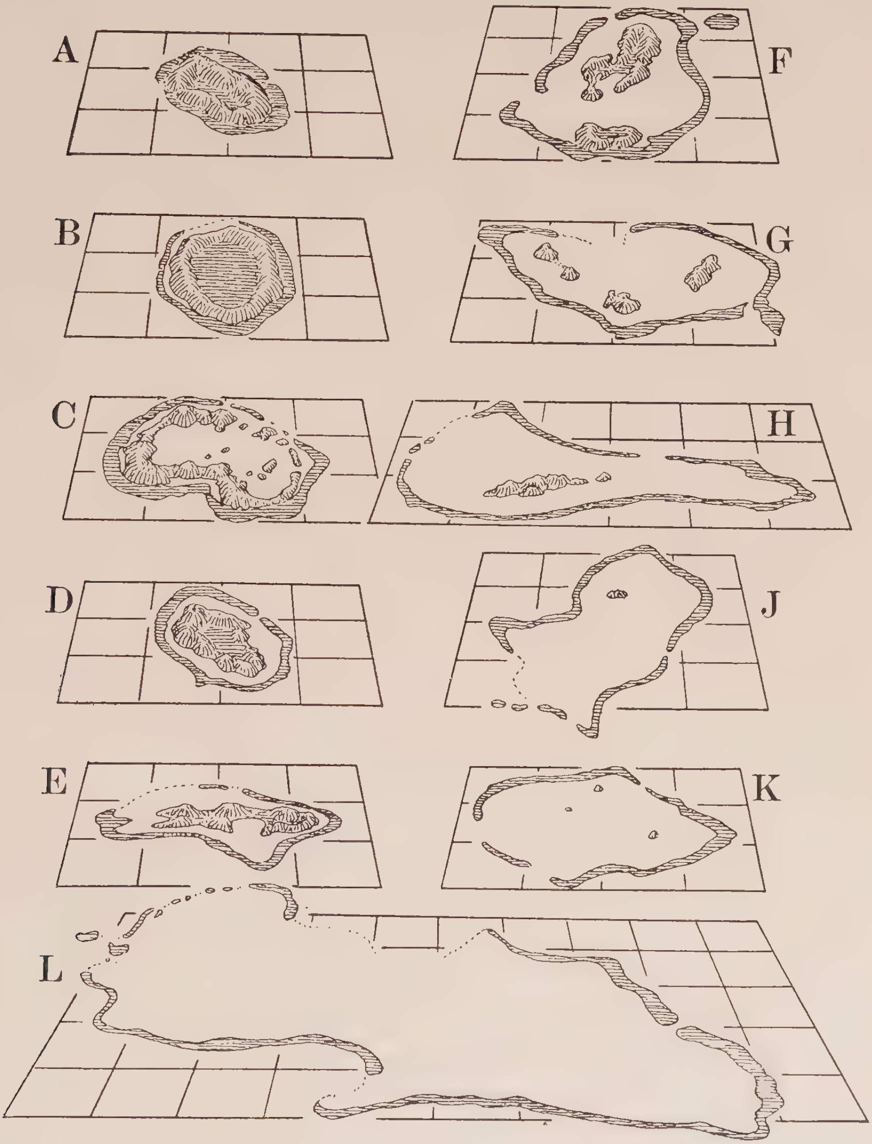


FIG. 32—Diagrams of elevated and dissected atolls in eastern Fiji; the small squares are 2 miles on a side. *A*, Naiau; *B*, Kambara; *C*, Fulanga; *D*, Tuvuthá; *E*, Namuka; *F*, Ongea; *G*, Yangasá; *H*, Oneata; *J*, North Argo; *K*, Reid; *L*, Great Argo.

no subsidence . . . but . . . that the cutting down of volcanic islands by wave-action and currents, has had a greater share in providing suitable bases for coral atolls than any other process of nature" (1897, p. 393).

In the fourth place, if atoll-lagoon floors are underlain by completely abraded rock platforms, almost-atoll and barrier-reef lagoons ought to be underlain by less completely abraded platforms; and in that case their central islands ought to be strongly cliffed. But such islands are rarely cliffed; hence their lagoons are not underlain by abraded platforms, and hence the occurrence of abraded platforms beneath the lagoons of sea-level atolls is very unlikely. That the great Seychelles bank also is not underlain by a platform of abrasion is made probable not only by its vast extent but also by the form of the few islands that rise from it. Mahe, the largest, is a fine example of a well dissected, granite mountain, with non-cliffed, tapering spurs dipping gently beneath the sea between well-defined embayments. Good views of these forms are given by Keller (1898, p 158), Chun (1900, p. 426), and Gardiner (1906, p. 457). Such an island therefore gives no indication of being an abrasional remnant. It is only in the marginal belts of the coral seas that reefs are associated with stack-like residual islands which, like Balls Pyramid (Fig. 89) between New Zealand and Australia, rise from the central area of submarine banks, as will be more fully told in Chapter VIII. The fact that strongly cliffed islands do occur in the marginal belts with precisely such forms as should occur in the coral seas also, if Wharton's theory were correct, taken with the fact of their absence in these seas, shows that it is not correct.

In the fifth place, a good number of elevated and more or less dissected atolls in southeastern Fiji show no flat platform of volcanic rocks at depths of 30 or 40 fathoms beneath their limestone crests; and thus the presence of such platforms beneath non-uplifted atolls is made extremely improbable. These elevated atolls are described in some detail by Gardiner (1898, p. 467), who recognizes them to have been sea-level atolls before their elevation, and by Agassiz (1899), who disputes that origin, as will be further told later; a number of them are drawn in perspective in Figure 32, with somewhat exaggerated vertical scale, from Agassiz' charts; the squares in the perspective network are two miles on a side. The islands are arranged in sequence from *A* to *L* according to the amount of erosion they have suffered, and all of them are described in one of my earlier papers (1917). The first, *A*, Naiau, 580 feet in rim height, is still practically intact. The seventh, *G*, Yangasá, is reduced to several small limestone islands, the highest of which still rises 390 feet from sea level, while its lagoon has a depth of nearly 20 fathoms; thus from island top to lagoon floor is a vertical measure of about 500 feet, or over 80 fathoms. As the eroded island is surely lower than the original atoll rim and as the lagoon floor is somewhat aggraded, the vertical measure between the atoll rim and whatever foundation underlies the lagoon floor must have been more than 80 fathoms. Surely, therefore, no level platform of volcanic rock could here have stood only 40 fathoms below the original reef. In view of all these considerations, Wharton's theory of normally abraded platforms is unacceptable.

Gardiner's Theory of the Maldive Atolls

The most extreme extension of the process of marine degradation is found in the explanation which Gardiner has proposed for the peculiar reefs of the Maldive archipelago in the Indian Ocean, not far southwest of India. This explanation, which involves deep currents, shares an unsatisfactory peculiarity of Wharton's theory of wave-abraded platforms in assuming that the agency first acts destructively on still-standing islands and thus prepares a foundation—here assumed to be over 100 fathoms deep—for reef growth while reefs are absent and that organisms then take possession of the prepared foundation and grow up to the sea surface (1902, 1903, 1903–06). Gardiner's knowledge of the zoölogical aspects of the coral reef problem is exceptionally extended and intimate, but his geological conclusions are unsatisfactory. Although he accepts the submergence of a large land area between India and Madagascar in Tertiary time, he arbitrarily decides that "this depression is not the same as the slow and long continued subsidence, postulated by the upholders of the Darwinian theory"; and then "seeing the absolute impossibility of subsidence affording any explanation" for barrier reefs and atolls, he concludes, as above intimated, than "an almost flat plateau at a depth of 140 to 170 fathoms was at one time formed by the erosion and denudation of an original land mass or more probably series of masses," and that the present shoals and reefs of the Maldives were afterwards built up on it by organic agencies (1903, pp. 205, 206).

This explanation appears to me untenable on several grounds. First, because of the arbitrary rejection of subsidence in association with atoll growth; second, because of the excessive depth to which destructive marine processes are supposed to act; and third, because of the tacit exclusion of early reef growth from the original land masses in order that marine processes shall destroy them. There is no valid reason for believing that the subsidence of a large land area—Gondwanaland—between India and Madagascar might not here and there, now and then, have gone on at such a rate as to permit the formation of fringing and barrier reefs around its sinking slopes and eventually of atolls above its submerged summits. Although the general absence of well-developed reefs from that part of the ocean suffices to prove that, on the whole, subsidence was too rapid to be counterbalanced by reef upgrowth, the presence of the Maldives, Laccadives, and other reefs, to say nothing of many submarine banks or drowned atolls, indicates that reef growth did sometimes counterbalance subsidence.

As to the great depth to which Gardiner supposes submarine degradation to have acted, some ground is provided by the dredgings made under his direction by a Percy Sladen Expedition to the Indian Ocean, concerning which he has prepared several reports. Thus on finding that the deep slopes around the banks of the Chagos group of drowned atolls "re-

sembled almost a hard concreted road," he concluded that "the bottom between the banks . . . was everywhere current-swept even down to 1000 fathoms" (1906, p. 324). The possibility that these bare slopes are original lava surfaces, down upon which the talus from the reefs that crown the banks has never extended, does not seem to have been considered. In any case it would go against the consensus of geological opinion to believe that deep marine currents could reduce a Maldive land mass to a depth of 150 fathoms; and it should, I believe, go against zoölogical opinion to believe that corals did not form reefs on the shore of that land during its subsidence and prevent its degradation; for surely reefs are formed on practically every clean-swept, subsiding shore in the Indian Ocean today. It may therefore be said again that the exclusion of protecting reefs from the shores as well as the postulated stability of the original land mass, which Gardiner assumes to have existed on the site of the Maldives, seems arbitrary and unacceptable. When the Maldive atolls are described near the close of this book, another scheme for their production in which subsidence at varying rates is an essential factor will be presented, together with reasons for thinking it reasonable; but it will not be regarded as demonstrated.

Summary

Nine alternative theories, apart from Darwin's own alternatives, have been reviewed in this chapter. Some of them, like Rein's and Semper's, were based on limited experience with coral reefs; others, like Agassiz' and Gardiner's, on exceptionally wide experience. The theories vary greatly in their postulates and processes, but in their presentation they all have two characteristics in common; namely, defective deduction of consequences and hence a very incomplete confrontation of consequences with facts. Perhaps the chief reason for these deficiencies is that nearly all the inventors of these theories had been trained more in biological than in geological science. If they had heard of Dana's confirmation of Darwin's theory in the matter of the embayed shore lines of barrier-reef islands, they discredited it; if they had met the geological term, unconformity, they made no application of the principle that it embodies. Some of them attributed overmuch work to marine abrasion, and none of them gave due attention to subaerial erosion. Their theories cannot be accepted, because the consequences are strongly contradicted by the facts.

Nevertheless, as intimated at the opening of this chapter, the student of coral reefs is indebted to all these inventors of alternative reef-forming theories, because as a result of the advocacy that they have given to one conceivable process of reef formation or another, the whole problem of reef formation has been more closely and critically scrutinized than it would have been if none of these theories had been invented. The true theory will be all the more worthy of belief because these various alternative possibilities have been considered and excluded.

CHAPTER V

THE GLACIAL-CONTROL THEORY OF CORAL REEFS

Outline of This Chapter

The object of this chapter is to analyze the Glacial-control theory of coral reefs, in the form that it has been given by Daly. The theory contains much that is novel and at least one new process of noteworthy value, and its successive steps are argued with much more geological competence and logical continuity than any other theory of coral reefs since Darwin's time; it must therefore be here set forth in considerable detail. It is diametrically opposed to the theory of upgrowing reefs on subsiding foundations and is indeed the only serious rival of Darwin's theory; it must therefore be examined with close attention. The strength of the theory lies in the large body of well ascertained facts upon which it is based and in the coherence of the argument by which it is elaborated. Its weakness lies in the lack of independent verification for its long series of postulated conditions and deduced consequences.

Theories Involving Changes of Ocean Level

A profitable discussion arose in the last third of the nineteenth century regarding the possible explanation of upgrowing reefs and embayed shore lines by a rise of ocean level around still-standing reef foundations, instead of by a subsidence of reef foundations in an ocean of constant level. This aspect of the problem was briefly presented by several writers with particular regard to changes of ocean level due to the withdrawal of ocean water during the accumulation of continental ice sheets and its return during their melting in the successive Glacial and Interglacial epochs of the Glacial period. The same phase of the discussion was later given somewhat fuller consideration by Penck (1894), and in 1910 and afterward the discussion was still more elaborated by Daly. Penck concluded that, in view of the surprisingly uniform depth of many atoll lagoons and in view of the prevalence of embayments in continental coasts, the ocean must have formerly stood for a considerable period from 100 to 200 meters below its present level and that its rise may have been associated with the climatic changes of the Glacial period (1894, Vol. 2, pp. 581, 658–660); yet in a later account of the Great Barrier Reef of Australia, he explained its upgrowth as well as the embayments of the Queensland coast back of it by assuming a subsidence of the reef foundation (1896, p. 19). Let it be noted, however, that as to the prevalence of valley-mouth embayments in continental coasts, formerly glaciated coasts should not be included, because their embayments are largely due to glacial erosion below sea level. The production of embayments elsewhere has undoubtedly been favored

by the Postglacial rise of ocean level; but inasmuch as some of the embayed valleys appear to have too great a rock-bottom depth and too great a sea-level breadth to have been excavated during the relatively brief epochs of lowered sea level in the Glacial period, either a former higher stand of those coasts or a more prolonged lower stand of the ocean than is provided by Glacial control must be appealed to in giving opportunity for the erosion of such valleys. After their erosion either a strong lowering of the coasts or a strong rise of the ocean must be appealed to in accounting for their submergence. In so far as such a rise of the ocean is due to suboceanic crustal upheaval, that must have taken place chiefly outside of the coral seas, because the islands there found so very generally show signs of submergence, like that of continental coasts. Also, in so far as such a rise of ocean level has taken place at all, there will be so much less subsidence of reef foundations to account for.

It should be borne in mind in this connection that if either a rise or a fall of ocean level is caused by a movement of the ocean floor, that movement must be as many times greater than the change of surface level as the area moved is smaller than the whole ocean area; while, on the other hand, if an island changes its level, the measure of ocean-bottom movement beneath the island will be practically the same as that of the island change; the difference is only the small alteration of ocean level due to the movement of a small area of ocean bottom. A pertinent quotation may be here introduced from Darwin, who, after citing Dana to the effect that the Paumotu atolls in the east-central Pacific have recently suffered a slight emergence, added that, if this view "should hereafter be confirmed, the question will arise, seeing how immense an area has thus been affected, whether those geologists are not right who believe that the level of the ocean is subject to secular changes from astronomical causes" (1874, p. 171); that is, he briefly contemplated the need of explaining the Paumotu emergence by ocean sinking instead of by island rise; but he did not pursue the idea further. It will be shown in the sequel that not all the Paumotu atolls have emerged; hence their change of level must be ascribed to local upheaval and not to a eustatic lowering of ocean level.

Daly's Glacial-Control Theory

With one exception none of the authors who have considered the association of Glacial changes of ocean level with the formation of coral reefs gave more than a brief discussion of the possibilities thus opened up. By Daly alone have the additional elements of changes of ocean temperature and their expectable consequences been formulated (1910, 1915, 1916, 1917, 1919); by him also was the name "Glacial-control theory" proposed for the new explanation of coral reefs thus provided. The theory in briefest form is essentially as follows:

The depth of the larger barrier-reef and atoll lagoons is thought to be

so nearly uniform that it cannot be accounted for by aggradation over subsiding foundations; it demands some process acting in a way to produce level, sub-lagoon rock platforms at a uniform depth of 40 or 50 fathoms. This process is found chiefly in abrasive action by the lowered ocean—that is, in low-level abrasion—on stable islands during the Glacial period. In order to give opportunity for such abrasion, it is held that the waters of even the torrid ocean were then sufficiently chilled to weaken or inhibit the growth of reef-building organisms, so that the emerged reefs could be cut away and the islands behind them attacked. Waves then working at a depth of 30 or 40 fathoms below present sea level would completely truncate the older, worn-down and deeply weathered volcanic islands, which had already been partly truncated at normal ocean level in earlier reef-free periods, and would also cut benches at the same standard depth around younger islands that were then still mountainous and more or less reef-fringed. On the margin of the platforms and benches thus produced the existing atoll and barrier reefs would grow up and their lagoon floors would be more or less aggraded as the warming ocean rose to normal level in Postglacial time. As above intimated, in order that the lagoon depths should remain nearly uniform, the reef foundations must be prevailingly stable.

Each step of this argument will be given fuller statement in the following pages, largely in the author's own words, and each step will be then commented upon as to its acceptability. The quoted passages are from Daly's fullest statement of 1915, unless otherwise specified. Let it be noted in advance that the term "platform" in Daly's various essays is sometimes applied to actual lagoon floors and sometimes to the hypothetical surface of abrasion that is assumed to lie beneath them; also, that the term "plateau" is occasionally used as synonymous with platform in both senses. The effort will be made elsewhere in this book to use the explanatory term "platform" only for inferred surfaces of marine abrasion, extended outward by detrital embankments; actual shoals, discovered by soundings, will be called lagoon floors if they are reef-enclosed, or banks if not so enclosed.

Let it be noted also that, from the beginning of Daly's discussion, the existence of sub-lagoon rock platforms of abrasion is assumed with so great confidence that it is rather to the means of their production than to the evidence for their existence that his argument is directed. Thus, in his earliest essay, attention is given chiefly to the "origin of the broad plateaus [platforms] on which the reefs have been built" (1910, p. 300). Their existence is again confidently assumed in the statement: "That the plateaus are due to erosion [of preëxistent islands], coupled with the deposition of the eroded material as an advancing submarine talus, seems to be the preferable explanation" (1910, p. 303). The alternative hypothesis that lagoon floors have been built up to a smooth surface of fairly accordant shallowness over foundations of whatever form and of

whatever depth nowhere receives detailed consideration; it is rather briefly dismissed as impossible. Inasmuch as such an origin for lagoon floors, in my view, seems eminently probable, the depths of those floors which Daly regards as accordant and the assumed occurrence of abraded rock platforms beneath them will be closely examined.

Uniformity of Lagoon Depths

As to the uniformity of lagoon depths: "The bathometric relation of platform [lagoon floor] to reef is normally so constant in all three oceans that a general explanation of reefs in terms of crustal movements seems impossible" (1915, p. 162). "The existence of the broad plateaus, their accordant relation at present sea-level, and the impossibility of explaining them by any cause other than prolonged marine action, are the supreme facts exphasized in this paper" (p. 222; also p. 237). The uniformity of lagoon depths is tested by the tabulation of many examples, from which it appears that large lagoons are usually deeper than smaller ones, evidently because, as already noted, they are more rapidly aggraded by inwashed detritus (pp. 183, 192). "Since probably not more than 5 m. to 25 m. can be allowed for the thickness of the Post-Glacial calcareous veneer in the wider lagoons, the accordance of [the hypothetical] platform depths for the wider lagoons and reefless banks seems clear" (p. 192).

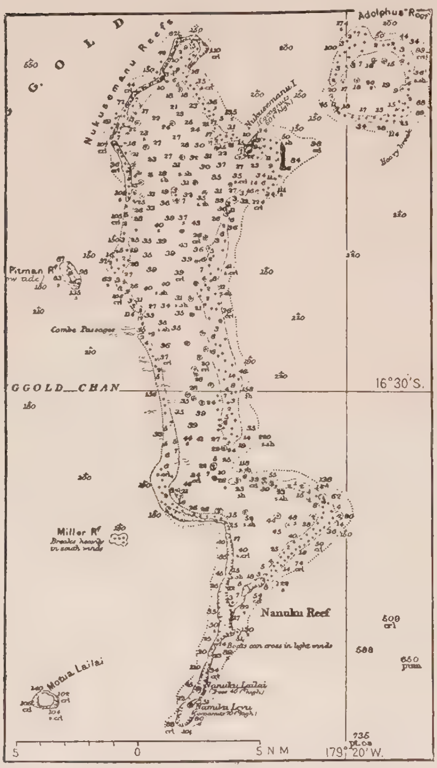


Fig. 33—The long Ringgold Atoll in northeastern Fiji; HO 2851.

Diversity of Lagoon Depths

The following comments may be made on the quotations of the preceding paragraph, first, as to the occurrence of greater depths than 50 fathoms in lagoons and on banks; second, as to the diversity of depth in lagoons of similar size. The large almost-atoll of the Exploring Isles in eastern Fiji, about 25 miles in longer diameter, has the exceptional depths of 70, 80, and 90 fathoms in its eastern part, apparently the result of re-

cent tilting, as Agassiz implied (1899, p. 93). The reef of the Ringgold or Nanuku Isles, a long and narrow atoll (Fig. 33) measuring 23 by from 3 to 5 miles in northeastern Fiji, has in spite of its narrowness a depth of 52 fathoms in its southern part; much of the reef fails to reach the surface, thus suggesting recent depression. The reef which fringes the southwest side of Viti Levu, the largest of the Fiji Islands, becomes a barrier on the west coast; and as it advances farther northwest it first narrows, next disappears from the surface, and then ends as a sunken barrier where its lagoon floor has sloped down to a depth of 58 fathoms. A reef reappears farther on but soon disappears a second time. Farther north the outermost one of the small Yasawa Islands, well fringed, appears to be bordered by an extensive bank on which two soundings, each of 80 fathoms and each reporting "sand, coral," are charted, the border of the bank not being defined. These variations of lagoon and bank depth seem clearly to indicate recent subsidence of increasing measure to the northwest: yet Daly takes the islands of the Fiji group to be stable.

Examples from other parts of the Pacific are as follows: The great almost-atoll of Truk, about 35 miles in diameter in the western Carolines, has according to the latest German chart two soundings of 58 fathoms. The little almost-atoll of Clipperton Rock in the eastern Pacific, only two miles in diameter, has a sounding of 52 fathoms. The imperfectly sounded barrier-reef lagoon of Vanikoro, a 12-mile island in the Santa Cruz group (Fig. 136) referred to by Darwin as indicating recent subsidence, has a sounding of 56 fathoms in its narrow lagoon. At the northwestern end of Isabel, a large island in the Solomon group, the shore line is much embayed, and a barrier reef, which reaches the sea surface farther to the southeast, there becomes a "sunken barrier" with depths of 5 or 10 fathoms on its crest, and the lagoon inside of it, imperfectly charted, has three soundings of 52 fathoms. At the southeastern end of the same island a smooth shoal extends off the embayed coast with depths of 80 to 90 fathoms nearer shore than its marginal depths of 44 and 52 fathoms. Inside of a partly submerged barrier reef near the southwest coast of New Georgia in the same group, a sounding of 60 fathoms is charted. Rua Sura, a three-mile atoll near Guadalcanar in the Solomon group, has the unusual depth of 49 fathoms in its small lagoon. The great lagoon of the Tagula barrier reef in the Louisiade Archipelago, east of New Guinea, illustrated in one of my earlier articles (1922a), is divided into a smaller northern and a larger southern basin by a chain of small islands, and each basin is nearly 50 fathoms deep. The lagoon along the eastern part of the southern coast of New Guinea has a width of from 5 to 20 miles, inside of the "sunken barrier," and there the maximum soundings along a stretch of 150 miles are 40, 45, 54, 59, 45, 43, 42, 41 and 43 fathoms; to the east and west, where the barrier reaches the sea surface, the lagoon depths are less. North of New Guinea, Ninigo, 13 by 18 miles, has a mile-wide barrier-reef flat and lagoon depths of 52 and 55 fathoms.

Two imperfect barrier reefs on the east coast of Celebes, the large northeastern member of the Dutch East Indies, enclose lagoon floors with depths of from 60 to 85 fathoms in one case and from 53 to 61 in the other. Kalukalukuang, an imperfect atoll 60 by 35 miles, west of Celebes, has depths down to 99 fathoms. The exceptionally great depths of these lagoons, especially those with imperfect reefs, appear to me to indicate that subsidence has there been more active than is usually the case in the

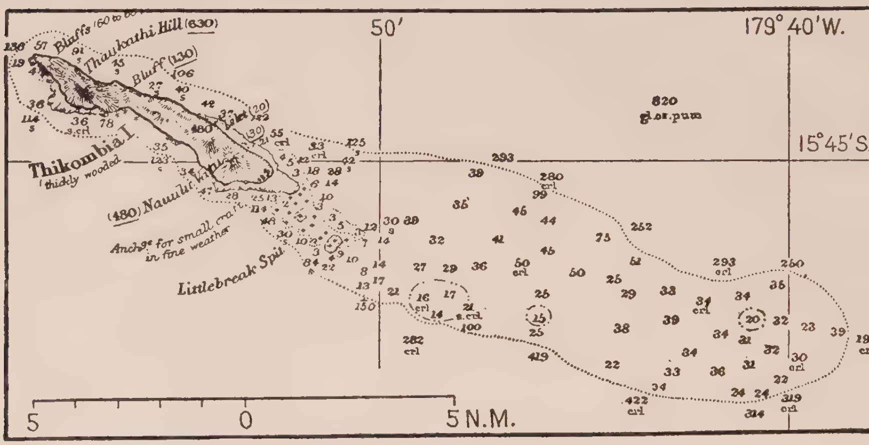


FIG. 34—Thikombia Island and Bank, northeastern Fiji, HO 2851.

open Pacific, but not that the islands of the open Pacific have long been stable. Some of the examples here cited are recognized by Daly (p. 208) as indicative of recent differential movements, as will be noted in the third following section.

As to submarine banks, which will be more fully treated in Chapter XVII, a small one adjoining the little island of Thikombia in northeastern Fiji—not far northeast of the unusually deep lagoon of Budd reef, mentioned below—has depths of 50 fathoms, as shown in Figure 34; and similar depths are charted on the rimless bank at the northeastern end of the larger island of Taveuni, southwest of Budd reef, as in Figure 102. A bank around Fauro, a small island in the northwestern part of the Solomon group, has soundings of 70 or 80 fathoms back of shallower soundings near the bank margin. A bank adjoining the island of Tana Jampea, in the Flores Sea, south of Celebes, has central depths of 49, 50, and 56 fathoms with a shallower rim; yet lagoons of ordinary depth occur in the same region. A rimmed bank, 26 by 11 miles, east of Gilolo in the same archipelago, has depths of 101 and 103 fathoms. The great Macclesfield Bank, a drowned atoll in the China Sea, has depths of 55 and 60 fathoms inside of its submerged reef rim. Tizard and Vanguard banks, farther south, have depths of 48 and of 50 and 57 fathoms. The imperfectly rimmed bank that borders the northwestern side of Palawan,

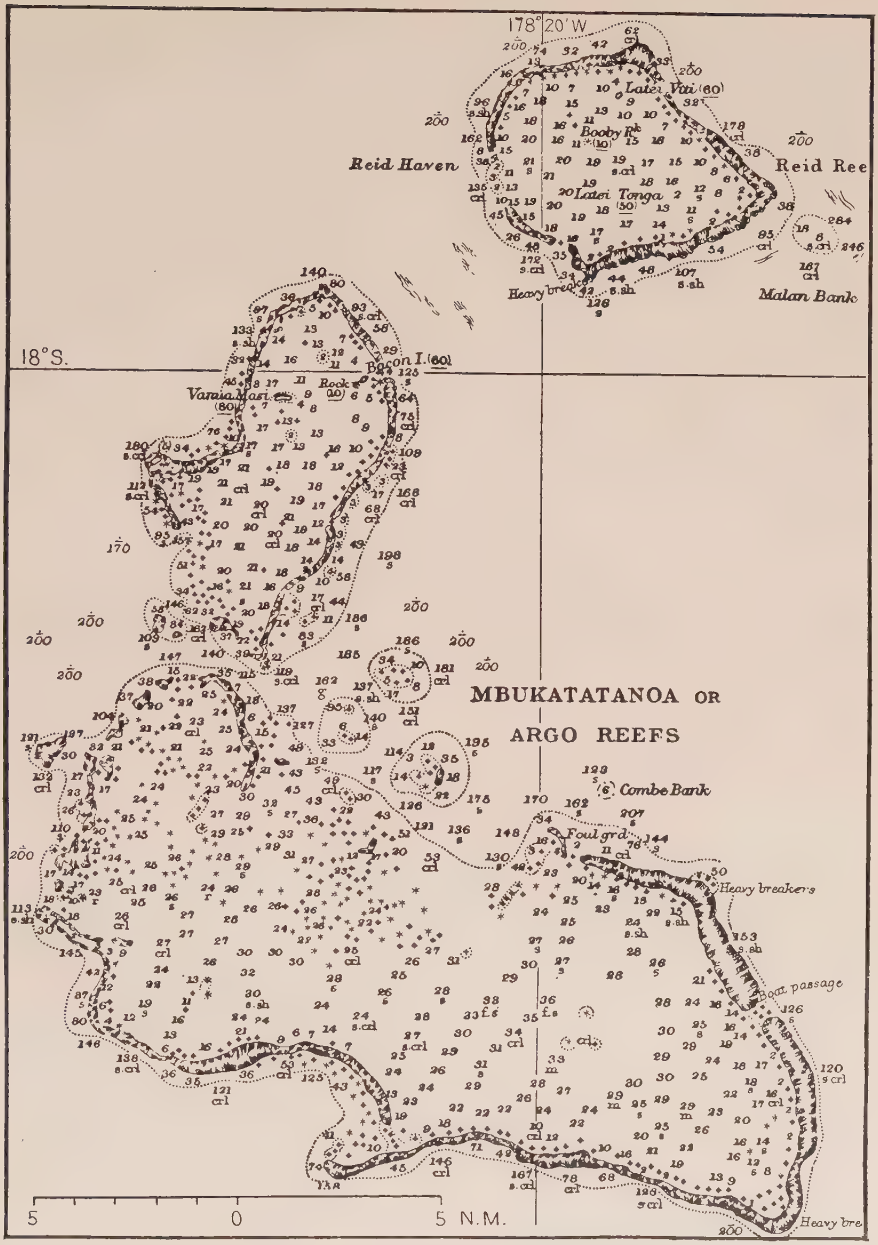


FIG. 35—Three good-sized atolls in eastern Fiji; HO 2851.

the long southwestern member of the Philippine group adjoining the China Sea, has a maximum depth of 60 fathoms near its mid-length, as if the bank had been warped down there more rapidly and to a greater extent than near its ends, where it is shallower. The well surveyed bank

that surrounds Tutuila, the American member of the Samoan group, has a number of soundings from 60 to 68 fathoms inside of a belt of smaller depths, which is taken by Daly and others to represent a submerged barrier reef.

The bank southwest of Vavau, the northernmost island of the Tonga group has depths of 65, 69, and 84 fathoms inside of lesser depths. The Haapai bank (Fig. 217), farther south in the same group, has depths of 60 and 62 fathoms; and the Namuka bank (Fig. 217), still farther south, has depths of 63 and 70 fathoms. A small three-mile bank, about 100 miles southwest of the Tonga group, has five soundings, 88, 88, 89, 91, and 93 fathoms, with gradual increase of depth shown by other soundings; two of the soundings on the bank report "coral." This is a significant example on two grounds; the soundings appear to define the minimum depth fairly well; and there is abundant space in neighboring, unsounded oceanic areas for the occurrence of many similar banks. About thirty miles southwest of this bank, a single sounding of 171 fathoms reports "coral, rock." This is less significant, because an isolated sounding does not define the minimum depth of a bank. In the Indian Ocean the large Saya de Malha bank has central depths of from 60 to 70 fathoms, gradually increasing, according to Gardiner (1905a, p. 44), to 200 fathoms before falling off to greater depths.

Turning now to examples of diverse depths in lagoons of similar size: Ringgold, or Nanuku, and North Argo atolls (Figs. 33 and 35), both in eastern Fiji, have about the same breadth of five miles, although the first is much longer than the second; but the maximum depth of Ringgold is 52 fathoms, while that of North Argo is only 21. Budd reef, west of Ringgold, an almost-atoll enclosed by an unusually narrow reef rim measuring 12 by 6 miles across, has a maximum depth of 47 fathoms; and two lagoons of smaller breadth, imperfectly enclosed by barrier reefs near the islands of Rambi and Taveuni, not far west of Budd reef, have depths of 47 and 49 fathoms; yet Ngele Levu Atoll, not far to the northeast, measuring 13 by 7 miles and therefore a little larger than Budd reef, has a maximum depth of only 16 fathoms; and the maximum depth of the much larger Great Argo Atoll (Fig. 35), measuring 22 by 8 miles, some distance to the south, is only 36 fathoms. Still more striking is Christmas Atoll, far off in the Pacific, HO 1839, 15 miles across, with a three-mile, windward-reef flat and a lagoon only 2 to 4 fathoms deep.

The above examples, which might be increased in number, appear to be less suggestive of uniformity than of diversity in lagoon depths; and the diversity seems to be better explained by unequal subsidence of unstable reef foundations, varying in place, area, rate, amount and date, than in any other way. Such variations of depth seem to be regarded as accidental discrepancies in the third exposition of the Glacial-control theory: "The theory by no means excludes the occasional discovery of exceptional depths even inside barrier and atoll reefs, where constructional

hollows—drowned valleys, fault-troughs, volcanically formed depressions —have not yet been filled with detritus" (1919, p. 154). It would seem reasonable to include also recent subsidence and recent upheaval, along with the much less probable causes that are specified, as possible causes for unequal lagoon depths in the above-cited examples and in many others, especially as there is abundant independent evidence of recent upheavals and subsidences in the associated island groups. Indeed, in view of Daly's recent acceptance of subsidence as the cause of the 60-fathom depths around Tutuila in Samoa (1924, p. 123), and of his earlier acceptance of tilting as the cause of the westward increase of depth in the Tonga banks (1915, p. 208), it would seem necessary to accept subsidence as also the cause of the exceptional depth of the little atoll of Clipperton Rock in the eastern Pacific, of the great Macclesfield Bank in the China Sea, and of the Saya de Malha bank in the Indian Ocean. Yet if subsidence has there been operative, it can hardly be excluded from a smaller contribution to the considerable depths of the Tagula and the Truk lagoons and many others.

Degradation of Lagoon Floors

It may here be noted that, in so far as reef-enclosed lagoon floors have similar depths, there are two seldom-considered processes which may have contributed to bringing about that similarity. One process is solvent erosion, or solutional degradation, which must have taken place not only on reefs but also on lagoon floors wherever they were emerged by the lowering of the ocean in the Glacial epochs. This process must have deepened any lagoons that were in Preglacial time unduly shallow, as I have elsewhere explained (1923c). The efficacy of the process will depend largely on the amount of rainfall; and that is not large on low-standing islands in the trade-wind belts, although it may be considerable in the shifting belt of the equatorial calms. Yet, while marine abrasion acts linearly and while subaerial erosion acts areally, solvent erosion acts cubically, in that it is applied not only to the surface but to every underground fissure that is penetrated by rain water; and moreover such erosion will not be much retarded, after the fashion of subaerial erosion, as its work nears completion; it will, perhaps, be accelerated by reason of the intricately irregular and cavernous excavations that have by that time been opened to its application. There is, however, at present no way of knowing how rapidly this process really acts on emerged lagoon floors; yet in so far as it was operative in the Glacial epochs, it must have worked to deepen shallow lagoons; and, furthermore, lagoons that were exceptionally deep must then have been given opportunity to become shallower. A second process that tends to bring about a similarity of lagoon depths is the exportation of lagoon floor silt either in suspension or in solution by outflowing currents, especially at time of storms, as has been explained in an earlier chapter. The quantitative value of this

process is unknown, but in so far as it has any value, it would seem to act against the shoaling of large lagoon floors to less depths than 40 or 30 fathoms, while it would be little operative in deeper lagoons.

The upshot of these suggestions is that, while variations of lagoon depths are small compared to the great depths of the ocean around them, they are so great among themselves that they cannot be regarded as uniform enough to demonstrate a long prevailing stability of reef foundations, against which so many barrier-reef islands give abundant evidence.

Stability of Reef Foundations

As to the stability of reef foundations, little is said in Daly's first paper of 1910; but in the fuller statement of the Glacial-control theory in 1915 long enduring stability is emphasized. It is at the same time explicitly recognized that "there has been Recent crustal warping in certain oceanic areas affected by coral reefs" and that "perfect crustal stability in the intertropical zone during the Pleistocene and Recent periods is obviously not implied in the Glacial-control theory" (pp. 160, 222); but it is also said: "Most of the reef platforms, like many banks situated outside of the coral seas, have such forms, dimensions, and relations to the sea-level that they appear to have originated during a long period of nearly perfect stability for the general ocean floor. . . . Submarine topography [of lagoon floors] seems impossible of explanation without assuming crustal quiet beneath most of the deep sea during at least the later-Tertiary and Quaternary periods" (p. 162). "Crustal stability is necessarily postulated only for the parts of the coral-sea areas where *broad* platforms [lagoon floors], about 75 m. below sea-level, are now found. For those areas the assumption of prolonged crustal stability, except for minute oscillations, seems absolutely unescapable. . . . Upholders of the subsidence theory will naturally question that the ocean floor has been undisturbed for a time long enough for the preparation of the reef platforms by erosion and deposition. . . . The work demands much of the later Tertiary, as well as the Pleistocene period, and thus, during several million years, the relation of sea bottom and sea surface was not significantly changed" (p. 221).

In a later essay, the demand for long-enduring stability seems at first reading to be relaxed, for it is there announced that "in general, the Glacial-control theory demands crustal stillstand no more prolonged or but little more prolonged than that demanded by any other theory of reefs yet published"; also, that the theory "demands general stability of the earth's crust in the tropical belt [not "during several million years," as above quoted, but] only for the last few hundreds of thousands of years, during which, however, local instability has been pronounced." More especially, that "the full duration of effective crustal stillstand . . . need not be any longer than the 'long stationary period' or a 'long interval of

rest' postulated by Darwin to explain the flatness of lagoon floors and other associated features" (1919, pp. 159, 155). But when it is recalled that the "long stationary period" which Darwin suggested for the Society group, but not for other groups, was only long enough to account for "the shoalness of the lagoon channels around some of the islands [Moorea?] the number of islands formed on the reefs of others [Borabora?] and the broad belt of low land at the foot of the mountains" [in Tahiti] (1842, p. 128), it must be seen that such a period was very short compared to "the last few hundreds of thousands of years." Yet closely associated with Daly's statements quoted above is another: "The hypsometry of the wider lagoons and banks, reef-rimmed or not, suggests stability for most of the tropical-sea floor since at least the late Miocene" (1919, p. 159), and this again surely implies stability for "several million years." The pauses during intermittent subsidence as postulated in Darwin's theory do not approach any such duration as that.

Hence, instead of regarding the passages above cited from the third exposition of the Glacial-control theory as indicating a relaxation of the demand for crustal stability, they are perhaps better interpreted as involving a greatly exaggerated conception of Darwin's "long stationary period." The same may be said of a similar passage in Daly's recent essay on "The Geology of American Samoa" (1924, p. 126).

Instability of Reef Foundations

It must be first pointed out, in commenting further on the preceding passages concerning prevalent and long continued stability of reef foundations, that this fundamental postulate of the Glacial-control theory is based wholly on the accordance of lagoon depths, and not on independent evidence derived from the geological history of reef foundations. In the case of the barrier reefs that are included in Daly's tables, the foundation islands are held to have been stable at least during the formation of the reefs, whatever the earlier history of those islands or of other near-by islands may have been. Thus 12 islands in Fiji are instanced as having been "nearly or quite stable in recent time," because they all "have well defined, coral-crowned shelves" [lagoon floors] at proper depths (1915, p. 208). Yet among these islands are Viti Levu ("the north side") and one of the Exploring Isles, the lagoons adjoining both of which have, as above noted, inclined floors that descend very gradually to the unusual depths of 80 or 90 fathoms.

It must also be noted that, while instability is fully admitted by Daly in a number of instances where its recognition is called for by the slant or the unusual depth of a bank, instability thus demonstrated is not looked upon as invalidating the evidence elsewhere derived for stability from accordant lagoon depths, where proof to the contrary is wanting. One of my chief reasons for not regarding general stability established by such evidence is that the examples of atoll and barrier-reef lagoons cited by

Daly include a good number from Fiji and the southwestern Pacific, where the geological history of the neighboring mountainous islands is strongly indicative of instability. In view of this, it may be urged that, if the lagoons in a region of geologically determined instability have normal depths, the occurrence of similar depths in the atoll lagoons of the central Pacific region of undetermined geological history should not be accepted as affording convincing demonstration of its stability.

Only 11 normal atolls, 2 almost-atolls, 2 atolls of so small a size that they have no central lagoon, and 3 barrier reefs are instanced in Daly's tables from the scores of atolls in the central Pacific, a region which is supposed to have enjoyed "a long period of nearly perfect stability." The failure to cite other atolls is probably because their lagoons are not well sounded. Yet 11 atolls and 13 barrier reefs are instanced as having stable foundations in Fiji, in spite of the fact that this group is recognized (1915, p. 224) as standing in the disturbed region of the western Pacific. As these Fiji lagoons are found to have depths that are regarded as accordant with the depths of the mid-Pacific lagoons, that accordance is taken to indicate that the Fiji reef foundations as well as those in the mid-Pacific have been stable in late geological time. But the geological history of the Fiji group, as deciphered by Andrews (1900), Woolnough (1903, 1907), Foye (1918), and Brock (1924), shows that the group has long been unstable. Foye's observations in particular include several striking instances of recently uplifted barrier or atoll reefs that rest unconformably on subaerially eroded volcanic foundations. Further evidence to be presented in Chapter XVI from my own observations will show that among the best-defined movements of the Fiji group is a westward-advancing, wave-like anticline which has recently traversed the very area where the Fiji atolls included in Daly's tables most abound.

Several other regions, the atolls in which should also be considered, are known to be of pronounced instability, as will be shown in later chapters. Among these are the Louisiade and the Solomon groups east of New Guinea, the central area of the Dutch East Indies, and the China Sea. A good number of atolls thereabouts, some of them having ordinary lagoon depths, will be cited in the next-to-last chapter of this book. Not many of them are found in Daly's tables, probably because relatively few have been well sounded; yet, whatever the depths prove to be when they are better measured, the fact that atolls occur there shows that their reefs have maintained themselves at sea level in spite of whatever subsidence has taken place and hence that stability is not necessary for atoll production. If the depths prove to be exceptionally great, which is not likely in view of the ordinary depths already charted in a number of examples, that will suggest that the independently inferred subsidence has been relatively rapid; if the depths are of ordinary measure, that will not disprove the independently inferred subsidence but will merely show that lagoon aggradation has been fairly well able to counterbalance it.

A corollary of this view leads to the conclusion that the rate of lagoon-floor aggradation is, in the long run, not much slower, even in large lagoons, than the contemporary upgrowth of the enclosing reefs, although it may have been much slower than the rate of Postglacial ocean rise, during which the previously formed reefs, more or less damaged by erosion during their emergence, were repaired and given their present forms.

Thus interpreted, it is perhaps permissible to regard the average rate of subsidence of reef foundations postulated in Darwin's theory as having long been, over the relatively placid mid-Pacific at least, so slow that its occurrence is not altogether incompatible with the almost perfect stability postulated in the Glacial-control theory. In any case, the many examples of instability found among barrier-reef islands of decipherable geological history give evidence not only that such reefs have been formed in association with the subsidence of their foundations but also that the stability of atoll foundations, the geological history of which is not decipherable, is very improbable. The similarity of the lagoon depths in a not inconsiderable number of atolls which occur near the unstable archipelagoes of the western Pacific to the lagoon depths of the more numerous atolls of the central Pacific leads to the same conclusion, as above noted.

Lowering of the Glacial Ocean

The amount by which the Glacial ocean was lowered in the Glacial period is calculated by Daly from the estimated volume of continental ice sheets. It is concluded that "at the time of maximum glaciation, the tropical seas probably had an average level which was 60 m. to 70 m. (33 to 38 fathoms) lower than at the present time" (1915, p. 174). Confirmation for this conclusion was found in the essay of 1910 in the depths of the embayments by which the shores of reef-encircled islands are indented: "The Pleistocene deepening [lowering?] of the inter-tropical seas is precisely of the amount required to explain the drowned valleys of the volcanic islands which are now surrounded by barrier reefs. . . . The maximum depth charted for these drowned portions of the valleys appears never to exceed 45 fathoms" (1910, p. 306). But this accordance obtains only if the observed water depth of the embayments and not their estimated rock-bottom depth is considered. The rock-bottom depth, as inferred from a reasonable downward prolongation of the bay-side spur slopes near the bay mouths on a number of islands that I visited in 1914, is much greater than the water depth; it is in some cases as much as 100 fathoms or more. Yet the true measure of submergence that produced the embayments is usually even greater than the rock-bottom depth thus inferred near the bay mouth; for the true valley-mouth depth is found at the original shore line of the island, which must lie where the downward prolongation of the inter-bay spur crests meets the downward extension

of inter-spur stream beds, and therefore farther seaward than the present bay mouths, as will be more fully explained on page 133.

Furthermore, the principle of maximum embayment, to be explained in the next chapter, shows that a well embayed, mountainous island must, in gaining its long embayments, have subsided sufficiently to submerge a considerable fraction of its original height and therefore a somewhat larger fraction of its surviving height. It is my belief that the measure of submergence thus demanded is frequently much greater than that provided by the Postglacial rise of ocean level, to say nothing of the insufficience of the duration of the Glacial epochs for the excavation of the embayed valleys to their observed width.

Daly's second essay recognized that the rock-bottom depth of island embayments is greater than their water depth and gave limited recognition also to island subsidence as a cause of embayments but apparently restricted the area of such subsidence to the western Pacific and its date to Tertiary time: "Some bays of the central islands [of barrier reefs] in the western Pacific are explained by the sinking of those islands," because that part of the ocean was the scene of "the Tertiary fragmentation of the Australasiatic continent" (p. 227); but "a similar explanation cannot be admitted for [the embayments of barrier-reef islands in] most of the coral archipelagoes" (p. 224), because they do not lie in the disturbed area of the Pacific. The extent of the "disturbed area of the Pacific" is, however, not known: its extent is the very question at issue. Some islands in the central Pacific—for example Tahiti in the Society group—have embayed and more or less delta-filled valleys, the rock-bottom depth of which appeared to me to be decidedly greater than the measure of ocean lowering above given, as will be told in chapter XI. Borabora in the same group has embayed valleys of such visible breadth and inferred depth that their excavation by low-level erosion seems out of the question. The Society group must therefore be included in the "disturbed area."

It may next be pointed out that if the production of embayments by island subsidence is excluded from "most of the coral archipelagoes," and if the low-level abrasion of their Preglacial reefs, as further discussed in the next section, is insisted on, one is led into a quandary. For in the absence of island subsidence the embayed valleys must be ascribed to low-level erosion in the Glacial epochs; and, if those epochs endured long enough for the erosion of mature valleys, they must have endured long enough for the low-level abrasion, during the inhibition of reef growth, of strong sea cliffs also, the upper faces of which should still be visible above normal ocean level; but such cliffs are wanting except in the case of a few young islands. A simple escape from the quandary can be found: it is that the islands here referred to were reef-protected even during the Glacial epochs and that their embayments are chiefly due to the partial submergence of previously excavated valleys by subsidence; but this leads us from the Glacial-control theory back to Darwin's theory.

Uncertain Measure of Ocean Lowering

Another test of the measure of ocean lowering in the Glacial period that I have attempted to apply is found in the depth of banks that occur around certain strongly cliffed islands on the margin of the coral seas, to which fuller reference will be made in Chapter VIII. It may be here briefly noted that such banks commonly have depths of 10 or 20 fathoms near the islands and of 40 or 50 fathoms at the outer margin, where a steep descent is made to deep water. Evidently, if the lowered ocean stood 30 fathoms below present sea level when the cliffs of those islands were cut, the outer margin of the embankment built of detritus from the cliffs must have stood about 40 fathoms lower still, or from 70 to 80 fathoms below present sea level; and the moderate depth of the present bank must be due to Postglacial aggradation with detritus partly supplied by abrasion as the ocean was rising, partly supplied by calcareous organisms; for little cliff cutting has been done on the islands since the ocean rose to its present level. If so great a measure of Postglacial aggradation seems improbable, then the depth at which the cliff-base platform was cut should be reduced. This may be done by assuming that the ocean was truly depressed by as much as 30 or 35 fathoms at times of maximum glaciation and that platform cutting and embankment building went on at such times at corresponding depths; but that the later stages of glaciation, witnessing a slow rise of ocean level, were marked by a gradual rise of the level of abrasion and that, as the platform was cut farther and farther back, the detritus then supplied went to aggrade the lower surface of the earlier abraded area. It is perhaps for this reason that the banks above alluded to have moderate depths near their cliff base. But, if so, large atoll lagoons ought to have shallow centers; and they have not.

Rate of Glacial Changes of Ocean Level

The rate at which changes of ocean level took place in comparison with the rate of intermittent subsidence, which as postulated in Darwin's theory was counterbalanced by reef upgrowth, may be briefly inquired into. Let it be assumed that there were at least three Glacial epochs, in each of which the ocean sank 30 fathoms, and also that the duration of each ocean fall and ocean rise was about equal to the duration of each of the intervening Glacial and Interglacial epochs. Then there must have been 11 intervals since the beginning of the first Glacial epoch, during six of which a total ocean rise and fall of about 1200 feet was accomplished. This means that if these changes had been going on at the same rate during all of the intervals, the total change would have been 2200 feet. If, as some glacialists believe, the total duration of the Glacial epochs was only a fifth of the entire Glacial period, the total change of ocean level would have been greater still. But surely not even the most ardent believer in

Darwin's theory assumes that the subsidence of reef foundations and the upgrowth of reefs in the open Pacific has averaged anything like 2200 feet since the opening of Pleistocene time, although local displacements at some such rate may have taken place in the very unstable Australasian region.

The conclusion here reached is that such Glacial changes of sea level as have occurred have been much more rapidly accomplished than the usual changes of island level in the coral seas; nevertheless, the measure of the Glacial changes remains undetermined. If it were as much as 30 or 40 fathoms, then a very considerable measure of bank and lagoon aggradation, a much greater measure than Daly allows, is demanded in the brief period of Postglacial time; so great an amount, indeed, as to give new evidence that lagoon aggradation may not be much slower than the ordinary rate of island subsidence and reef upgrowth, as has already been inferred on other grounds.

Low-level Abrasion

The following passages concerning low-level abrasion will indicate the area over which this process, so essential in the Glacial-control theory, is believed to have acted. The first quotations are from Daly's earliest essay: "The reef corals were, of course, not exterminated during the Pleistocene, but they may well have been restricted to such warm, more or less enclosed seas as those of the East Indian region. The imagination suffers, therefore, no painful stretch in our considering that, throughout the Glacial period, extensive marine abrasion in the equatorial belt was possible because of a general lack of growing coral reefs in the open ocean. . . . There is no reason to doubt that the volcanoes here considered [mid-ocean volcanic islands of large size] are of many different ages, possibly from the pre-Cambrian to the Tertiary" (1910, p. 304). The older islands, "emerging because of the negative movement of sea-level, were, therefore, generally low . . . and, above the new sea-level, were composed largely of weak material. Exposed on all sides to abrasion by the open ocean, we may safely assume that . . . the Chagos Bank, by far the most extensive of the plateaus here considered (sixty miles by ninety miles), could have been reduced to the Pleistocene sea-level in about 50,000 years" (1910, p. 305).

The following passages are from the fuller statement of 1915, first regarding Preglacial preparation for low-level abrasion in the Glacial period: The Glacial-control theory "does not imply that any large proportion of the total erosion suffered by oceanic islands was accomplished during the Glacial period, but merely that the reef platforms were then finally smoothed by the removal of thin veneers of relatively weak materials formed on the oceanic plateaus in Tertiary and pre-Tertiary time" (pp. 159, 160). "Presumably the majority of the Pacific-floor volcanoes are pre-Pliocene, if not pre-Tertiary in age. If this be true, the oldest volcanic islands, long before the Glacial period, must have suffered

peneplanation or great reduction and then decomposition by down-seeping soil waters" (pp. 176, 177). "The peneplanation of an oceanic island, initially as large and lofty as Hawaii, would produce a composite of volcanic and shell material about as extensive as the Macclesfield bank, one of the very largest coral platforms known" (p. 181).

It would thus seem to be argued, as will be more fully shown by quotations on the next following pages, that atolls and barrier reefs were rarely developed in Preglacial times, not because there is any direct evidence to that effect but because their development would not take place on stationary islands. Also that islands must then as a rule have been stationary because their still-stand is a necessary antecedent to their reduction to atoll-sized peneplains of deep-weathered rock; not that any such worn-down, deeply weathered islands are known to have existed but that they in turn are necessary antecedents to the production of sub-lagoon rock platforms by low-level abrasion. Yet here again not that any such platforms are known but that their existence is deemed essential in the explanation of smooth lagoon floors of moderate and accordant depths today. The argument is perfectly logical, and its successive steps are well enchained; but it must be unconvincing while so many of its steps remain without independent verification. It must remain all the more unconvincing because the assumption that good-sized volcanic islands not infrequently stood still in Preglacial time long enough to be peneplained seems to be so generally contradicted by the behavior of good-sized volcanic islands in recent time. For, as has already been intimated and as will be more fully shown in later chapters, the bays of the maturely dissected central islands within certain barrier reefs and the mountain-top islets in almost-atolls give good indication that the original islands have subsided at a rate not unlike that by which their initial summits have been worn down to their present subdued forms. Surely, the best means of learning the behavior of volcanic islands in Preglacial time is found in the behavior of volcanic islands today.

Glacial Reduction of Ocean Temperature

The cooling of the ocean in the Glacial period is inferred to have been of such measure that "it is not an extreme view to hold that practically the entire area now occupied by the oceanic archipelagoes and by the great barrier reefs of Australia and New Caledonia was, during the maximum Pleistocene glaciation, bereft of reefs growing rapidly enough to resist destruction by the waves" (1915, p. 169; see also 1910, p. 305, above quoted). The duration of these reef-forbidding conditions is thought not to have been seriously interrupted even during Interglacial epochs: "Wave abrasion began before the climax of the Kansan stage and continued without serious interruption until the Wisconsin climax—a period estimated as 280,000 to 900,000 years" (1915, p. 181).

In consequence of the long continued wave attack on previously worn-down and deeply weathered still-standing islands, the question is asked: "Is it too extreme to believe that a relatively smooth surface of abrasion was completed just below the last low, Pleistocene sea-level?" And the answer is: "Whatever doubt may exist as to the ability of the Pleistocene waves to develop so large a platform [as that assumed to underlie the Macclesfield bank], there can be little as to their power to truncate completely the *average* volcanic island which had been peneplained and deeply decayed before the Glacial period" (pp. 181, 182). The resulting surface would include a detrital embankment built out around the central area of abraded rock; both are included in the term platform (p. 179). As to the form and depth of the abraded platforms: "The facets [rock platforms cut by Pleistocene waves] cannot be perfectly smooth and level, nor even in the case of those due to the complete truncation of islands, are they all at the same depth below present sea-level. . . . In general the platforms should be at depths ranging between 60 and 100 m.," or 33 and 55 fathoms (pp. 182, 183). On the surfaces thus prepared, reefs grew up as the rising and warming of the ocean took place in Postglacial time.

While the reduction of weak-rock islands of no great size to platforms with central depths of about 35 fathoms does not seem beyond the accomplishment of low-level abrasion where it had opportunity to act, it is quite otherwise with the reduction of large islands to platforms on which, even after Postglacial aggradation, depths of 60 fathoms are still found, as is the case with the great Macclesfield and Chagos banks. Such reduction would demand that even their central areas had been cut down not only to lowered ocean level but some 30 fathoms deeper; and this could not have been done unless all the peripheral area was worn down deeper still. The long duration thus demanded not merely for the Glacial epochs but for their maximum phases seriously discourages the acceptance of the abrasional process in the form in which the Glacial-control theory sets it forth. I have given special consideration to this phase of the problem in an earlier essay (1918b).

Daly's later essay recognizes that the degree of continuity ascribed to Pleistocene abrasion in the two earlier papers was overstated (1919, p. 146) and gives new emphasis to the smothering of reef-building organisms by stirred sediments on banks during Preglacial and especially during Glacial time; and it also otherwise modifies the theory significantly. It is concluded that "the late-Pliocene reefs are thus considered to have been almost wholly of the fringing type. The younger fringes were narrow because of their youth. The older fringes were probably broader, but their widening had been kept comparatively slow, both by the narrowness of many shelves and because of periodic smothering of reef organisms by shelf sediment" (1919, p. 143). With the advent of the first Glacial epoch and the lowering of the ocean, "the stirring of shelf muds and sands must have been much stimulated"; hence, "the shift of sea-level, of itself

alone, entailed a rarely equalled destruction of corals and probably encrusting Lithothamnia as well. The combination of oceanic chilling and smothering by sediment could hardly fail to reduce coral life on most shores to a very low state, if not to extinguish it altogether" (1919, p. 144).

This significant departure from a main thesis of the earlier papers is again stated even more strongly: "Perhaps killing by wave-stirred mud and sand was more important than the fall of oceanic temperature" (1919, p. 158). It may be at once noted that the inferred process here emphasized is of doubtful application around reef-encircled pelagic islands. Their exterior profile is usually so steep that the shore belt would be kept free from sediments during the emergence caused by the Glacial lowering of sea level, and reef-building organisms would therefore continually transplant themselves downward as emergence progressed. Witness the numerous cases of more or less elevated pelagic reefs, along the shores of which fringing reefs are now growing; but this phase of the problem is hardly considered in Daly's essay, perhaps because barrier and atoll reefs are assumed to have been rare or wanting in Preglacial time.

On the other hand, an apparently contradictory consequence of fall of ocean level is next stated: "A specially notable effect of the lowering of sea-level during glaciation is seen to have been the shallowing of water on the [reefless] banks and shelves then existing, so that corals could take root on the edges of these submarine plateaus. In comparison, the platforms due primarily to Pleistocene abrasion are less important" (1919, p. 158). These modifications of the earlier form of the Glacial-control theory change it so greatly that it is hardly recognizable.

Evidence Against Low-level Abrasion

While several comments in the preceding pages on the argument there illustrated indicate my dissent from its conclusions, it should not be inferred that I dissent from the argument also. All pertinent arguments, and particularly an argument so original and ingenious as this, should be regarded as aids toward finding the true solution of a debated problem, such as the origin of coral reefs. The more varied and novel the quality of the arguments and the more critical their analysis, the better. It is because the successive steps of the Glacial-control argument are not sufficiently supported by independent tests that I find it unsatisfying; still more so when, on applying such tests as I have been able to devise, their evidence is found to be adverse to its conclusions. The chief tests of this kind that concern the postulate of the widespread abrasion of still-standing islands are briefly as follows:

Let it be agreed for the moment that the older volcanic islands of the coral seas have usually been stable for so long a time that they were peneplained before the Glacial period and reduced during the Glacial epochs to low-level platforms in sufficient number to serve as foundations for the numerous atolls of the Pacific coral seas. Then at least a fair

number of such platforms ought to be found in the cooler seas of the Pacific; but they are practically wanting there. If, on the other hand, volcanic islands have prevailingly subsided, then any that were long ago formed in the cooler seas would have been sunk out of sight, suffering more or less abrasion as they sank; and, as they are not memorialized by upgrowing atoll crowns, it is natural enough that they should not be seen today. This argument, which will be set forth more fully in Chapter

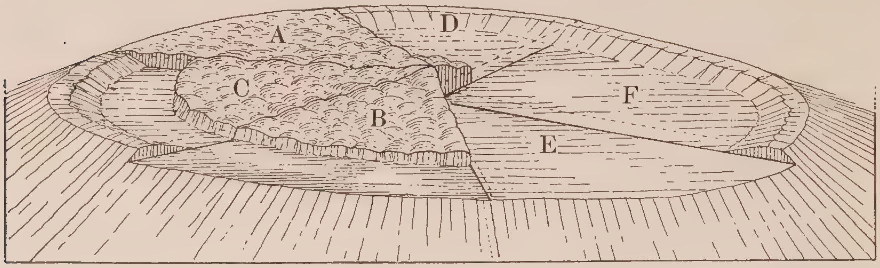


FIG. 36—Sector diagram to illustrate the degradation and abrasion of a still-standing island.

VII, is evidently based on the unproved assumption that at least a few volcanoes should have been formed in the cooler seas of the northern and southern Pacific, even if not so many as those which are believed to form the foundations of the numerous atolls in the central Pacific; but in any case the emptiness of vast areas in those northern and southern seas is very striking.

Let stability be again assumed, and let it be agreed once more that the older volcanic islands are so old that they were peneplained in Preglacial time and reduced to submarine platforms by low-level abrasion in the Glacial epochs; and also that the younger volcanic islands in the coral seas, now surrounded by barrier reefs, are so young that they have been but moderately dissected and that they were little cliffed while unprotected by reefs in the Glacial epochs. In this case there ought surely to be some volcanic islands in the coral seas of intermediate age, not old enough or not weak enough or not small enough for complete peneplanation and truncation, yet not so young and so resistant but that they should have been much worn down but not peneplained in Preglacial time, sector *A*, Figure 36, and much cut back, sector *B* or *D*, although not completely truncated, sector *E*, in the Glacial epochs. Such islands, now surmounting lagoon floors enclosed by barrier reefs, sectors *C*, *D*, should be rimmed with low plunging cliffs; but barrier-reef islands thus worn down and cliffed are unknown in the coral seas. Such cliffed islands as occur are still young and high. They do not owe their cliffs to abrasion determined by the widespread climatic conditions of the Glacial epochs, for near-by islands are not cliffed; they have been cliffed because of local, individual conditions which the islands themselves provide, as will be duly explained in Chapter XI.

FIG. 38—The embayed, non-cliffed southeast coast of Ngau and its fringing reef. (Photograph by Stinson, Suva, Fiji.)

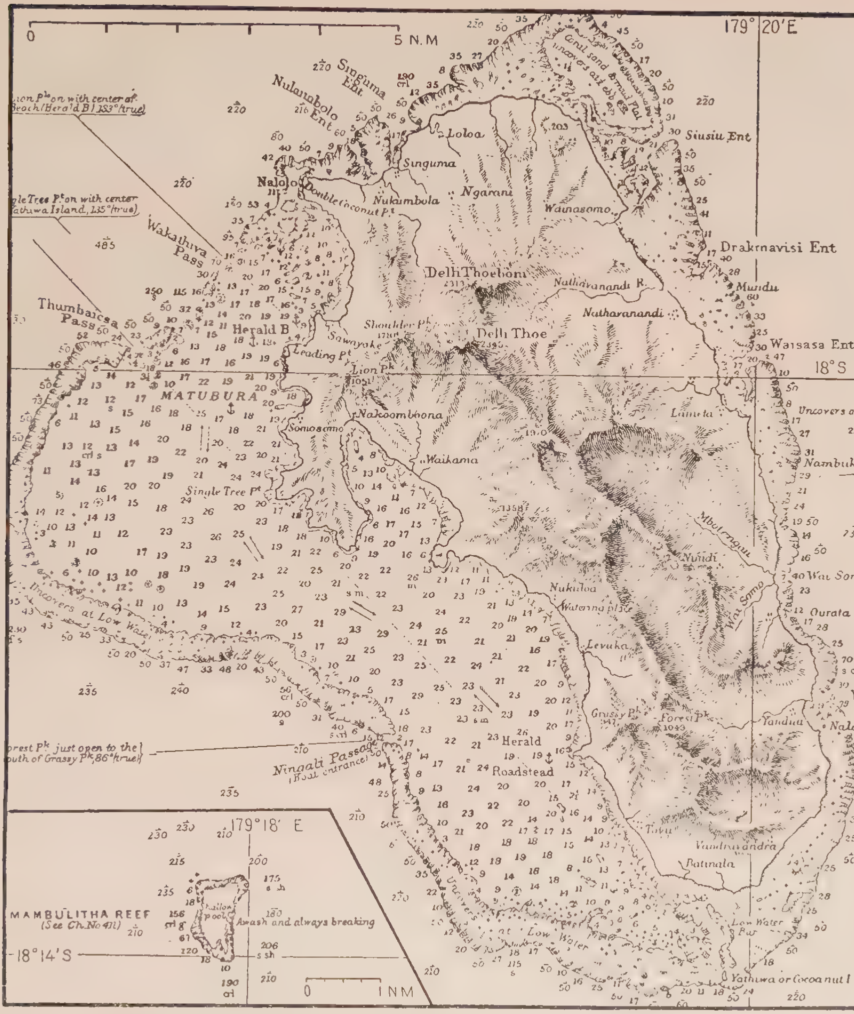


FIG. 37—Ngau and its unsymmetrical reef in central Fiji. Inset, a small atoll 5 miles to the south; HO 2859.

This argument seems to me of compulsory value, and all the more so for two special reasons. It is overlooked rather than disproved in the several expositions of the Glacial-control theory. And it is unexpectedly confirmed by the occurrence of plunging-cliff islands and islets surmounting banks in the marginal belts of the coral seas, of precisely such forms as should occur in the coral seas also if low-level abrasion had been operative there. This important point will be fully set forth in Chapter VIII.

A more direct argument against low-level abrasion is as follows: The southwest coast of Viti Levu, Fiji (Fig. 141), bordered only by a fringing reef, should have suffered partial truncation by low-level abrasion if it had truly been without reef protection in the Glacial epochs. Its vol-

canic hills are maturely dissected and of moderate height along the shore, as is well shown in one of Agassiz' photographs (1899, Pl. 43); but they show no shore cliffs whatever. It is hardly conceivable that plunging cliffs should not be seen here if low-level abrasion has truncated peneplained volcanic islands as large as the Chagos bank, 60 by 90 miles, in the Indian Ocean. The island of Ngau (Fig. 37), in central Fiji, may also be instanced to the same end; it is bordered along its eastern or windward coast of 10 miles by a fringing reef which falls off to deep water; hence it should have been exposed to strong abrasion in the Glacial

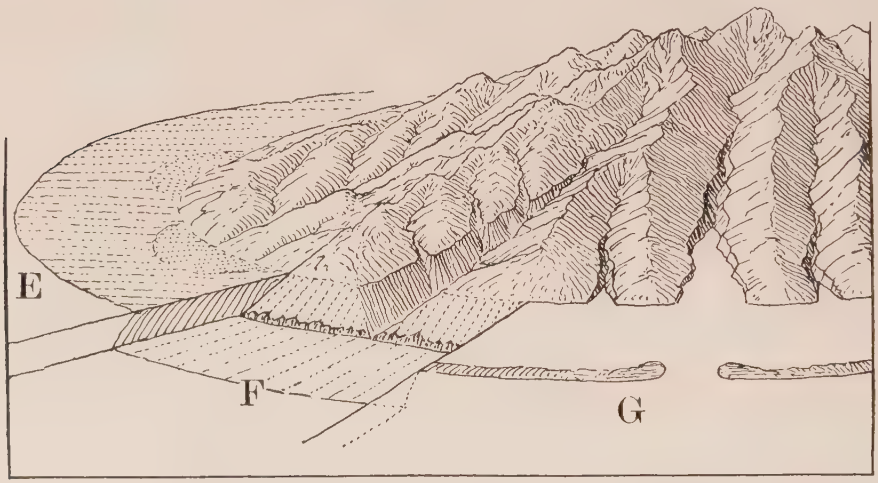


FIG. 39—Sector diagram showing effects of a short epoch of low-level abrasion on a still-standing island.

epochs if it were not then reef-protected; yet its spurs slope down gradually to the embayed shore without cliffs, as is shown in Figure 38. Various other examples of similar import might be given.

The theoretical aspects of the case for stable barrier-reef islands are further illustrated in Figures 39 and 40. Let an outgrowing reef, sector *E*, Figure 39, be emerged by reason of the lowering of the ocean in the Glacial period, and let low-level abrasion then operate only so far as slightly to cliff the volcanic slope after cutting away the reef, sector *F*. Then there will be time for the cutting of only young valleys by low-level erosion in the floor of the mature Preglacial valleys. When the ocean rises to normal level, sector *G*, the low cliffs will be wholly submerged and the embayments in the young valleys will be narrow and steep-sided; but such embayments are practically unknown. On the other hand, let low-level abrasion act for a longer time, sufficient to cut strong, mature cliffs, as in sector *F*, Figure 40. Then the associated work of low-level erosion may excavate mature valleys, which will be occupied, after normal ocean level is regained, sector *G*, by wide embayments with sloping sides between spur ends that are cut off in plunging cliffs. Wide embayments

are common, but plunging cliffs are rarely found. Rock resistance is immaterial here; for if hard rocks delay cliff cutting, they will also delay valley widening. As a matter of fact, barrier-reef islands ordinarily exhibit open embayments between sloping, non-cliffed spurs; and islands thus fashioned cannot be accounted for under the conditions of the Glacial-control theory. They demand the subsidence of maturely dissected islands, long protected from abrasion by encircling reefs.

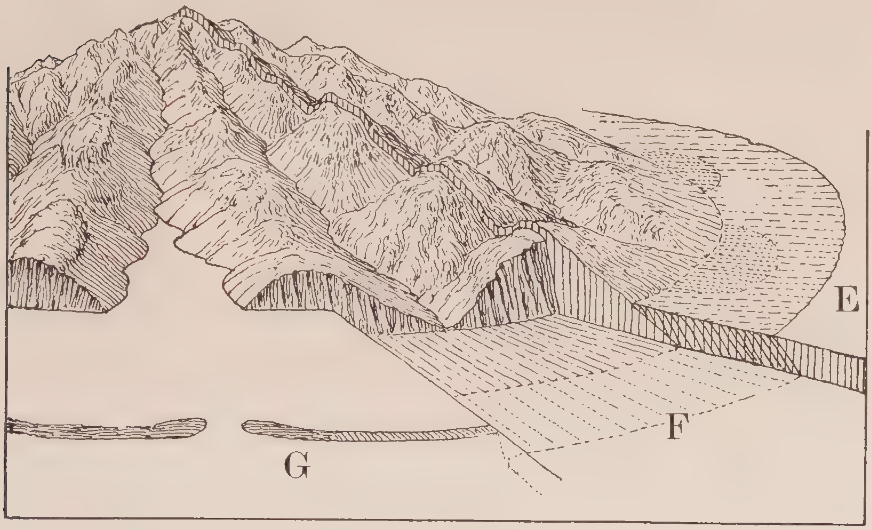


FIG. 40—Sector diagram showing effects of a longer epoch of low-level abrasion on a still-standing island.

It is true that Tahiti is, as already stated, for the most of its circuit rimmed with high plunging cliffs as well as dissected by deep-cut valleys; but islands thus cliffed are very rare in the coral seas, and other islands near Tahiti are not cliffed. It must therefore be concluded that the cliffing of exceptional islands was not conditioned by a widespread inhibition of reef growth caused by the lowering of ocean temperature in the Glacial period but by a local inhibition of reef growth such as is provided by the active downwash of detritus on young, non-embayed islands. On the other hand, non-cliffed, barrier-reef islands are, although by no means so numerous as atolls, widespread through the Pacific coral seas. They are known in the Solomon and Louisiade groups on the west, in the Carolines on the north, in the Society group on the east, and less distinctly in the Austral group on the south. It is therefore impossible to believe that a widespread inhibition of reef growth was caused during the Glacial epochs and hence equally difficult to accept the occurrence of abraded rock platforms under the numerous atolls of the Pacific.

On the other hand, let the non-cliffed spur ends of reef-encircled islands be considered along with the associated valley embayments, and let it be

understood that the embayments are frequently of greater breadth and depth than can be ascribed to low-level erosion during the Glacial epochs. It will then be seen, as above noted, that these non-cliffed, well embayed islands testify against long stability and against the exposure of their shores, unprotected by reefs, to low-level abrasion; that they indeed testify to a considerable submergence while their shores were continuously protected by encircling reefs. Like the argument illustrated in Figure 36, this argument is insufficiently examined in the Glacial-control theory. It is true that the number of barrier-reef islands in the central Pacific is not large; but nearly all that are found there are not cliffed, and all give evidence of submergence. The submergence in several of them appears, indeed, to have been so great that it can be explained only by subsidence. The few that are cliffed, being found near others that are not cliffed, must owe their cliffing to some local control, namely to the abundance of detritus downwashed to the non-embayed shores of their youth, and not to a widespread cause like climatic change.

Yet, inasmuch as the margin of the coral seas is determined by a limiting temperature of ocean water, it can hardly be questioned that the reefs situated in a marginal belt were killed and cut away in the Glacial epochs. Thus restricted, this active element of the Glacial-control theory is, in my opinion, the most original and valuable contribution to the coral reef problem that has been made since Darwin's early time. It remains therefore to evaluate, if possible, the breadth of the marginal belt of the coral seas over which low-level abrasion of dead reefs actually took place. This will be attempted in Chapter VIII.

Upgrowth of Reefs in Postglacial Time

The following passages present Daly's views as to the origin of existing reefs and lagoon floors. "With the late Pleistocene warming of the air, the warming of the tropical seas allowed the coral larvae, emanating from the limited reefs not entirely killed in spite of the Pleistocene chilling, to colonize the new, wave-cut platforms. . . . The fringing, barrier, and atoll reefs are thus explained as shallow crowns recently built up on wave-formed platforms. The hypothesis implies that barrier reefs and atolls have not necessarily characterized the warm seas of the pre-Pleistocene periods but represent physiographic forms due to the highly specialized effects of a Glacial period" (1915, p. 159). Hence, with the rise of the warming Postglacial ocean, "began the atoll and barrier reefs which are living because they were able to keep pace with the rising water-level. Some banks were, however, colonized too late or not adequately and have remained reefless to this day" (1919, p. 147). "The greatest possible thickness for these reefs is 110 m." (1915, p. 218). "The widths as well as heights [and hence the volumes] of the existing barrier and atoll reefs are of the proper size, if these calcareous rims originated on the plat-

forms in Post-Glacial time" (p. 219). As the reefs grew up the platforms were overspread with calcareous detritus, but "probably not more than 5 m. to 25 m. can be allowed for the thickness of the Post-Glacial calcareous veneer in the wider lagoons" (p. 192). The flatness of the lagoon floors thus produced is regarded "as no less than fatal to the Darwin-Dana theory" (p. 196). "After a fairly complete review of coral-reef literature, the writer is convinced that these theoretical consequences [as to small reef thickness] accord well with the facts so far published. That the existing reefs are mere veneers is the accordant testimony of Agassiz, Wharton, Semper, Gardiner, Guppy, and others of those who have studied recently elevated islands" (p. 219).

The original statements by the authors named in the last-quoted sentence cannot, in my opinion, be accepted as confirming the limited thickness of reefs in general as demanded by the Glacial-control theory. First, as far as Gardiner's articles are concerned, he in one connection infers a small thickness for Fiji barriers (1903, p. 204), yet he elsewhere infers a thickness of from 140 to 170 fathoms for the organic deposits below the Maldive atolls (p. 206), and that is five or six times the Glacial-control limit. Moreover, both of his inferences remain unacceptably hypothetical in taking no account of unconformable contacts or of embayed shore lines.

Second, it must be clear from the accounts of the views of Agassiz, Wharton, and Semper given in the preceding chapter that, emphatic as their statements are regarding the small thickness of existing sea-level reefs, those statements were chiefly inferences. Moreover, the inferences were not supported by evidence from the physiographic features of neighboring islands or coasts; yet, apart from borings, it is only from such evidence that trustworthy inferences as to the thickness of sea-level reefs can be gained. When that physiographic evidence is examined, it points strongly to the frequent occurrence of thick barrier reefs, as has been shown in Chapter II and as will be further shown in Chapter XIII.

Third, the true reason for the small thickness of various elevated reefs, such as those described by Guppy on certain islands of the Solomon group, is, as already explained in Chapter II, simply that the subsidence of their islands was too rapid to be compensated by reef upgrowth. Such reefs therefore do not bear at all on the question here under discussion. It is, to my reading, a serious reason against the correctness of the Glacial-control theory, that support for it is found in part in the acceptance of unwarranted inferences as to reef thickness, as if they were facts of observation.

As to existing barrier and atoll reefs being of such volume as should have been formed on platforms of about uniform depth during the Post-glacial ocean rise: It is true that many reefs are of similar surface dimensions, but also true that many others are of very dissimilar surface dimensions. Thus, in the Society group alone, the barrier reef on the windward

side of Raiatea is very narrow, while the barrier reef on the same side of Borabora has developed an unusually broad flat. Similarly in Fiji, Budd reef, an almost-atoll, is narrow and frequently interrupted all around its circuit; while the windward barriers of Ovalau and Mbengha in the same group are half a mile or more in breadth, and the latter is uninterrupted for over 20 miles. Among many other examples in various parts of the Pacific, mention may be made of Christmas Atoll, HO 1839, 15 by 12 miles, with a reef flat three miles wide on the east, a lagoon only two to four fathoms deep, and a single pass on the west side. Darwin properly regarded this atoll as having been long stationary. The great barrier reef of Tagula, east of New Guinea, is continuous for more than 40 miles on its windward curve and is nearly a mile wide for much of that distance; but several atolls not far away have slender and discontinuous reefs. In the China sea, Pratas atoll has a reef flat up to two miles in width, yet in the same sea the reefs on certain banks have not reached the ocean surface. Contrasts of this kind are abundant, and they are surely quite as consistent with the view that reefs have grown up on unstable foundations which have suffered unlike movements during an unspecified period of time, as with the view that the reefs have grown up on stable foundations of uniform depth in a limited and uniform measure of time.

But be it noted that the implication given in two quoted passages in the first paragraph of this section, to the effect that reefs built up from platforms of standard depth in Postglacial time should be of similar volume, is not warranted according to Daly's later reference to the same question (1919, p. 155). Various factors which would cause inequality of volume are there noted; yet variations in rate of subsidence are not included, probably because of the fundamental postulate of prevalent insular stability that inheres in the Glacial-control theory.

Aggradation of Lagoon Floors

The quotation given above in which the flatness of lagoon floors is said to be "no less than fatal to the Darwin-Dana theory" seems to me to imply a misconception of the processes by which lagoon floors are aggraded under that theory, as well as an insistence that the subsidence postulated in the theory must proceed so fast that the reef-enclosed depressions, or "moats" as Darwin called them, cannot be aggraded to flat floors while the subsidence is in progress. The same opinion is elsewhere expressed: "The comparative flatness of lagoon floors . . . is a feature expected on the Glacial-control theory and quite unexpected on the older theory, unless the auxiliary hypothesis of a very long pause in subsidence be accepted" (1915, p. 240). But it should be understood that we have no definite knowledge of the rate of subsidence, except that in the case of reef-enclosed lagoons it cannot have been faster than the rate of reef upgrowth; and no definite knowledge of the rate of supply of either inwashed or lo-

cally provided detritus in lagoons, except that it is known to be by no means insignificant; see the statement of Guppy above quoted regarding Keeling Atoll. It is therefore reasonable to believe that a deep potential moat can have been converted into a shallow, smooth, detritus-floored lagoon in the way Darwin outlined, provided subsidence was slow. Instead of being a "quite unexpected" result of the older theory, it was explicitly and warrantably announced as an expected result.

It might still be expected, however, as has already been pointed out in the account of Darwin's theory, that subsidence should have occurred somewhere at such a rate that a deep and unfilled moat should lie back of a barrier reef. This expectation would be perfectly reasonable if it were known that reef upgrowth is decidedly more rapid than lagoon-floor aggradation; but no such marked inequality between the two processes has been proved. On the contrary, the fact that sea-level reefs exist proves that whatever changes of island level have there taken place have not been faster than reef upgrowth. And the further fact that no very deep moat is anywhere found back of a barrier reef makes it probable that the processes of reef upgrowing and lagoon upfilling are not very dissimilar.

It might also be supposed that, under the influence of prevailing winds and of lagoon currents generated by them, a greater volume of detritus would be drifted to one side of the lagoon, thus making it shallower than the other; and so indeed Daly has argued (1916a). Yet a good number of drowned atolls, with reef rims 10 or 15 fathoms and lagoon floors 20 or 25 fathoms below sea level, have extraordinarily smooth floors, in spite of—or, more properly said, because of—the strength of the swell by which they are constantly traversed. Such atolls may have been formed according to Darwin's theory and then drowned by a rapid but small subsidence, or they may have been formed according to the Glacial-control theory by incomplete reef upgrowth from a still-standing platform of low-level abrasion; in either case their lagoon deposits now form a smooth lagoon floor. In fine, as far as I can see, the occurrence of smooth lagoon floors either within submerged or non-submerged reefs is no more fatal to Darwin's theory than it is confirmatory of its chief rival. The smoothness is, as Darwin saw, a natural result of aqueous deposition.

The Glacial-Control Theory in the Marginal Belt of the Coral Seas

Even if reefs were not killed during the Glacial epochs and cut away by low-level abrasion all over the open coral seas of the Pacific, they probably were, as above noted, killed and cut away in a narrow marginal belt of those seas. But, if the reefs in such a marginal belt were thus killed and cut away, they need not have been previously formed on still-standing foundations. It is entirely conceivable that reefs formed by upgrowth on subsiding foundations, according to Darwin's theory, may have been,

according to the Glacial-control theory, killed and cut away far enough to cliff their central islands in a narrow marginal belt of the coral seas, while the similarly formed reefs in the larger area of the true coral seas were not killed and cut away. It is therefore proposed to examine in a following chapter a combination of low-level abrasion, the most novel element of the Glacial-control theory, with the processes of Darwin's theory, in the hope that it may then be possible to measure the breadth of the inferred marginal belt by the occurrence of cliffed islands in association with coral reefs. The several above-cited examples of non-cliffed barrier-reef islands were taken from well within the coral seas; it is therefore eminently possible that certain other islands nearer the margin of those seas may show cliffed shores.

Vaughan's Studies of the Lesser Antilles

Vaughan's detailed studies in Florida and the West Indies have led him to explain the barrier reefs occurring there, and especially the bank barriers characterizing the Lesser Antilles, as upgrowths of small thickness from platforms that were recently submerged to moderate and nearly uniform depths. The platforms are regarded as having been antecedently produced, by processes that are as a rule not determined, at a time when the islands they adjoin stood relatively higher than now. A study of charts then induced this investigator to extend the same explanation to many reefs of the Pacific Ocean. The several announcements of this theory bear witness to a greater competence of its author in the combined discussion of the geological, paleontological, and physiographical aspects of the coral reef problem than is manifest in the statement of any other theory here analyzed.

The first statement of Vaughan's views included a brief but comprehensive summary: "The data presented on the relations of the barrier reefs of Florida, Bahamas, Cuba, and Australia showed that all of them stand on platforms submerged by rise of strand-line, and that the platforms are independent of the limits of living reefs. It is evident that the reefs are superimposed on platforms formed by other than reef agencies, and that reef-building organisms grow only in those places on the platforms where conditions for their life are favorable. The barrier reefs of Viti Levu, Fijis, and Tahiti, Society Islands, are similar in their relations—that is, they are superimposed on depressed platforms, the presence of which is independent of the reefs" (1914, p. 42). Another statement (1914d, pp. 32, 33) is equally explicit. A more general statement as to the Pacific is made two years later: "The relations around the Pacific islands off which barrier reefs occur are those of continuous platforms surmounted or margined by discontinuous reefs. These relations indicate the superposition of reefs on antecedent platforms which have undergone geologically Recent submergence" (1916, p. 45).

As to the origin of the platforms, which are also called banks, plains, plateaus, basements, and flats, several statements of later date may be quoted: "None of the American platforms were formed by infilling behind a barrier. . . . A review of the conditions under which the principal barrier reefs in the Pacific Ocean were formed leads to essentially identical conclusions. . . . Plains suitable for the growth of corals have been formed by subaerial and submarine deposition, and by both subaerial base-leveling and submarine planation. . . . Whether the flat was formed by marine planation, by alluviation and the building of a coastal flat, by base-leveling through subaerial erosion, by the formation of a submarine plain of deposition, or by any other special process, is unimportant, provided the flat be formed" (1919, pp. 319, 321, 322, 324). It is natural that, under this interpretation of barrier reefs and their platforms, Darwin's view that such reefs have deep foundations was rejected and an opposite view announced: "The width of a submerged platform bordering a land area is indicative not of the amount of submergence, but of the stage attained by planation processes" (1915, p. 60). It should be recalled that, in the account of barrier reefs under Darwin's theory, this view was presented in the case of islands of composite structure, and supported by two exceptional instances, as a possible but rare alternative to Darwin's view that the width of a lagoon is proportionate to the thickness of the enclosing barrier reef.

In discussing the changes of level that are associated with certain delicately terraced Lesser Antillean banks, which are taken to indicate emergence as well as submergence, the following statement is made: "What caused this lowering and subsequent rise of sea-level? As it affects a large area, it appears too widespread to be explained by local crustal movement. The changes in the position of strand line here noted are more reasonably explained by a lowering of sea-level due to the withdrawal of water in the Pleistocene ice epochs to form the great continental glaciers and the raising of sea-level after each epoch through the melting of the glaciers, but the volume of evidence supplied by this area is perhaps not large enough to justify a general conclusion as to the relations of Recent coral reef development to glaciation and deglaciation" (1916a, pp. 62, 63). Thus Vaughan's views are, in a certain measure, similar to Daly's.

Comparison of Atlantic and Pacific Reefs

It was not until after I had gained an understanding of the marginal belts of the Pacific coral seas, that I came to recognize the Lesser Antilles as included in the Atlantic marginal belt, first from a study of charts and later from a visit (1923). I was thus enabled to reconcile Vaughan's views based upon his studies of West Indian reefs with mine based upon studies of Pacific reefs. This reconciliation involves special interpretations of West Indian reefs, as follows.

The reefs of the Lesser Antilles are in my opinion imperfect, marginal-belt, bank barriers. They are barriers in the sense of rising some distance out from the shore of their islands; they are bank barriers in the sense of standing some distance back from the steep margin of their banks; and imperfect bank barriers in the sense of forming very incomplete circuits around the central islands and of frequently failing to rise to sea level. More important still, they are regarded as marginal-belt bank barriers because they are believed to rise from low-level platforms abraded in the Glacial period; the reason for this belief being that the spur ends of their central islands are cut off in plunging cliffs. The inferred platforms are, of course, not now observable; they are aggraded, and the resulting banks have as a rule a depth of about 40 fathoms at their outer margins, as if they had been built up on the platforms with respect to the waves and currents of present sea level.

The Lesser Antillean bank-barrier reefs, thus understood, are narrow and timid Postglacial novices. They are comparable with similar novice, bank-barrier reefs in the marginal belts of the Pacific but by no means comparable with the stalwart veteran barriers of the Pacific coral seas. Those great reefs rise in full strength to sea level and stand boldly over a steep descent to deep water. The barrier reefs of Cuba also appear to be true barriers, in the sense of bordering deep water, though they are hardly so vigorous as the typical barriers of the Pacific; hence Cuba may be regarded as standing in the coral sea of the Atlantic, as far as such a sea there exists.

Thus I have come to a partial agreement and a partial disagreement with Vaughan's views regarding the Lesser Antillean reefs. They appear, as he first explained, to be built up during the Postglacial rise of ocean level upon platforms in the production of which they—the present novice bank barriers—had no part. Inasmuch as the spur-end cliffs of the central islands plunge below present sea level, the platforms appear to be the product of low-level abrasion, which is one of the processes noted by Vaughan as competent to produce platforms. Furthermore, it is under this interpretation strictly true that the platforms were "formed by other than reef agencies," namely by low-level abrasion; but it is, I believe, also true that the mass on which abrasion acted to produce the platforms had been previously formed by coral reef agencies. It is not the abraded platforms, however, that are now found by soundings, but an aggrading cover of detritus which buries the platforms to an unknown but presumably small depth. A discussion of the reefs of the Lesser Antilles is given in much fuller form in my small book on those islands (1926).

Summary

Daly's several presentations of the Glacial-control theory have introduced an important process that is, I believe, destined to be of permanent

value in the coral reef problem; namely, the production of platforms by the low-level abrasion of circuminsular masses of coral reef and lagoon origin as well as by the slower abrasion of insular masses themselves, the encircling reefs of which were killed by the lowered temperature of the ocean in the Glacial epochs. But the area over which this process is thought to have acted appears to have been assigned too great a value in his theory, and the availability of the process has been limited in his discussion by its application only to prevailingly stable islands. On the other hand, the process of low-level abrasion is here regarded as having been inoperative over the greater part of the coral seas; for the absence of plunging cliffs on the great majority of barrier-reef and almost-atoll islands shows that their reefs were not killed. But the process is believed to have been very successfully operative on certain islands in the marginal belts of the coral seas, as will be told in Chapter VIII, although those islands are thought to have been about as unstable as their more numerous neighbors in the coral seas.

The moderate and fairly accordant depths of most reef-enclosed lagoons, upon which the Glacial-control theory is based, is here explained chiefly as a result of effective lagoon-infilling during the slow upgrowth of the encircling reefs on subsiding foundations. The occurrence of subsidence is independently proved in many cases, and the rate of subsidence is shown to have been slow by the fact that reefs have been able to grow up while it was in progress.

The absence of deep moats between barrier reefs and their central islands and the corresponding absence of deep basins within atoll reefs of pelagic regions may properly be taken to indicate that lagoon infilling is a much more active process than it is assumed to be in the Glacial-control theory, and indeed not much slower than reef upgrowth. The crustal stability demanded by the Glacial-control theory must therefore be regarded as of vastly longer duration than the brief "stationary period" which Darwin postulated for reef upgrowth and lagoon aggradation around certain islands. Indeed, the very slow subsidence which will fully satisfy Darwin's theory may perhaps be the equivalent of the prevailing crustal stability that is postulated in the Glacial-control theory for most of the coral seas of the world. And it is conceivable that the "renovating agency," namely subsidence, which Darwin thought was necessary to prevent the filling of lagoons, was helpfully supplemented by the exportation of silt from shallowed lagoons in non-Glacial times and by the degradation of emerged lagoon floors during the Glacial epochs.

The occurrence of atolls with ordinary lagoon depths, as far as they have been sounded, in the neighborhood of notably unstable island groups in the western Pacific is held to be of prime significance. For if lagoon infilling within upgrowing reefs has been successful in giving those lagoons ordinary depths where instability is well proved, the occurrence of ordinary lagoon depths in the atoll groups of the mid-Pacific, where nothing is

directly known about the behavior of the earth's crust, cannot be held to prove its long-enduring stability.

Of all the conclusions above reached, the one that seems to me most convincingly opposed to the Glacial-control theory is that which excludes from the coral seas the assumed process of low-level abrasion by which the supposed sub-lagoon platforms of those seas were produced in the Glacial period. Had this process been so effective as to provide platforms for the numerous atolls of the coral seas by the complete truncation of old, well degraded and deeply weathered volcanic islands, there ought to be a moderate number, at least, of less old, less degraded, and less deeply weathered islands which would be incompletely truncated; and as such they would now be characterized by plunging cliffs surmounting their barrier-reef lagoons. Although a number of islands show precisely such features over the banks of the marginal belt adjoining the coral seas, the barrier-reef islands of the coral seas are as a rule not thus characterized. The few barrier-reef islands that are cliffed are relatively young and owe their cliffs to a lack of defending reefs as determined by local, individual conditions provided by the islands themselves, and not to the widespread climatic conditions of the Glacial epochs.

CHAPTER VI

THE THEORY OF THE MARGINAL BELTS OF THE CORAL SEAS

A Classification of Pelagic Islands

It has been twice intimated in the preceding chapter that, even if the growth of reef-building corals were not inhibited over the whole extent of the coral seas during the Glacial epochs, such inhibition must have been effective over the marginal belts of the coral seas. In those belts the effects of low-level abrasion ought therefore to be recognizable in the occurrence of islands with plunging cliffs around their shores. It does not, however, follow that, in case such islands are discovered, they must have been characterized by the long-enduring stability that is postulated in the Glacial-control theory; it is clearly possible that temporary inhibition of reef growth might take place around subsiding islands as well as around still-standing islands. Hence it is now desirable not only to determine the existence and the width of the marginal belts in which islands show the work of low-level abrasion but also to discover whether the islands there situated have long been stationary or whether they have been intermittently subsiding.

It may be understood at the outset of this inquiry that three zones of the ocean—the coral seas, the marginal belts, and the cooler seas—should, as already suggested, possess pelagic islands of different forms. The coral seas should be characterized by islands that have been as a rule persistently protected by reefs; and such islands should not have been cliffed by low-level abrasion in the Glacial epochs. The cooler seas must be characterized by islands that have never been reef-protected and that have therefore been persistently attacked either by normal or by low-level abrasion ever since their eruptive construction. The intermediate or marginal belts of the coral seas should contain islands that have ordinarily been protected from normal abrasion by reef growth during the more genial climates of Preglacial, Interglacial, and Postglacial time but have been unprotected and exposed to low-level abrasion during the Glacial epochs. With these points in mind, a deductive classification of pelagic islands will be attempted in preparation for a study of existing islands, in the hope that it may then be possible not only to define the occurrence and width of the expectable marginal belts but also to determine whether the islands found there have been prevailingly stationary or not.

Nearly all pelagic islands are of volcanic origin. The chief exceptions to this rule are Viti Levu in Fiji, where continental rocks underlie a volcanic cover; New Caledonia, chiefly composed of continental rocks; and the small granitic islands of the Seychelles in the western Indian Ocean, which appear to be the last surviving summits of a vanished continental

area. These islands need not be considered for the present. Volcanic islands may be either in active growth by eruption or of completed growth. With actively growing volcanoes we shall be little concerned. Islands of completed growth are more important, and such islands may be subdivided, according to their behavior, as stationary, rising, or sinking. The islands of each of these three groups may be further subdivided according to the stage of their erosional development; and still again subdivided, as above indicated, according as their development is accomplished by the joint and continuous action of marine abrasion and subaerial erosion in the cooler seas where no coral reefs occur; or by subaerial erosion with limited marine abrasion in the warmer seas where coral reefs have long flourished; or by subaerial erosion combined alternately with strong and with weak or no abrasion in the marginal belts of the coral seas, where reefs were killed in the Glacial epochs but grew in non-Glacial epochs.

Stationary Islands in the Cooler Seas

Young stationary islands in the cooler seas are actively cut back by ocean waves in cliffs which rise around the island shore with increasing height as they retreat during the earlier stages of abrasion; and the cliffs are fronted with a gently inclined wave-cut rock platform that is extended outward by a detrital embankment to a marginal depth of about 40 fathoms. At the same time the upper slopes of the island are furrowed by the deepening ravines of consequent streams, which will mouth above sea level in hanging fashion in the cliff face, because strong-wave abrasion is faster than short-stream erosion. As time passes, the diminishing upland area above the retreating and height-gaining cliffs will be more and more maturely dissected and degraded, so that the original surface of the volcanic cone or dome will eventually be lost. At a late stage in the consumption of a large island the cliffs may slowly decrease in height because of the associated degradation of the central upland. After the upland is wholly consumed, the tops of the retreating cliffs will meet in a sharp crest of rapidly diminishing height, and the island may then be called a stack. In time the stack will be cut away, and only the rock platform surrounded by its detrital embankment, still with a marginal depth of about 40 fathoms, will remain. The rock platform may be very slowly worn down until its middle is almost as deep as its edge.

At any stage in the progress of these destructive changes, the advent of a Glacial epoch will transfer the locus of wave attack from normal ocean level to a lower level, which according to Daly's calculations lies about 30 or 35 fathoms below normal level. After working for a time at the lower level, a rise of the ocean will transfer the attack of the waves to normal level again. The locus of the line of wave attack during these changes of level may be represented, with much exaggeration of vertical measure, by the broken-line, looped curve of Figure 41, in which the initial slope

of the island, *ABG*, has been notched by a normal cliff and platform, *BDC*, and extended by a detrital embankment, *CF*. While the attack of the waves is applied at slowly lowering levels, *DE*, it will be relatively ineffective, because the waves will always be beginning their work over again; but while the ocean stands near its lowest level, *HJ*, and still better while it is rising slowly, *JD*, abrasion will be much more active. Hence, in the early phases of this work, little more than the detritus previously deposited will be removed; through the middle phases, *EHJ*, the normal

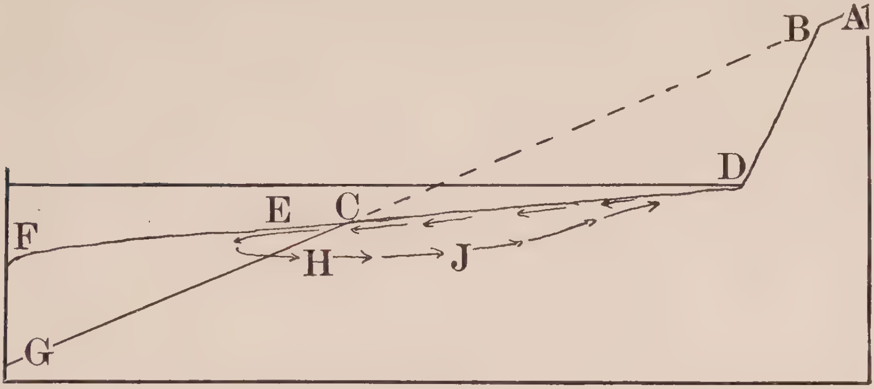


FIG. 41—Locus of abrasion attack during Glacial changes of ocean level.

rock platform will be less or more cut away, and the detritus thus supplied will go toward building out a low-level embankment with a marginal depth about 40 fathoms below the lowered ocean level; during the later phases, *JD*, a considerable amount of abrasional work may still be going on, and the detritus then provided will aggrade the earlier-cut, low-level platform and its embankment.

All through the time of lowered sea level the streams of the island will deepen their hanging valleys and will cut trenches across so much of the normal platform as is not consumed. The amount of change thus produced will depend largely on the resistance of the island rocks, the volume of the streams, and the duration of the Glacial epochs. If the valleys have been sufficiently deepened when the ocean rises again to normal level in an Inter- or a Postglacial epoch, they will be more or less embayed back of the island cliff line. During each rise of the ocean the low-level rock platform and its detrital embankment will be more or less covered with inorganic and organic detritus. The inner margin of the cover will lie against the undercut slope of the normal platform; or, if that platform has all been cut away, against the plunging cliffs of the central island. The aggraded cover will decline gently to its outer margin, which will tend to approach the normal depth of 40 fathoms. The surface thus built up over the abraded rock platform will be known as a bank.

The form exhibited today by an island thus modified will depend on its

original size, its age, and the resistance of its rocks. The successive profiles on the left side of Figure 42 represent the present forms of successively older islands, in which partly consumed normal platforms are undercut but not consumed by low-level platforms. The profiles on the right side of the figure represent the complete consumption of the normal platforms, so that the low-level platforms undercut and push back the normal cliffs. The low-level platforms are all drawn at the same depth, as if changes of ocean level had been of the same amount in all the Glacial epochs. If unlike changes are inferred, the lower platforms should be drawn at different depths, as in Figure 42, *A*. An island may be imagined to be so young, so large, and so resistant that its cliffs, surmounted by a furrowed cone or dome, are fronted by a narrow rock platform at normal level, outside of which lies a narrow, low-level platform with its embankment, the work of only the last Glacial epoch. If the island be of somewhat greater age, it will be more encroached upon by normal and low-level abrasion, so that its total platform width will be enlarged; but its shore will still be not well embayed, because the retreat of the cliffs will have cut away the distal part of its valleys of low-level erosion; and moreover, as the size of the island is reduced, its streams are shortened and their ability to deepen their valleys is lessened.

Indeed, a much consumed island may have lost the embayments which entered the shore line in its maturity and may have only hanging valleys over a non-embayed shore line in its old age. A large, ancient island may have been, in spite of its original size and resistance, completely truncated in a normal platform, which is in turn much encroached upon by a low-level platform; or, if of less size and resistance, the normal platform may have been completely reduced to a low-level platform with a correspondingly extended detrital embankment. The central depth of such a rock platform will be about 40 fathoms and the marginal depth of its embankment will be 70 or 80 fathoms below normal ocean level; but the bank that is built up on it by organic detritus with respect to normal ocean level will be shallower. The platform, thus cloaked with detritus, would constitute a permanent bank of moderate depth as long as the truncated island stands still.

Stationary Islands in the Coral Seas

A stationary island in the coral seas will at first suffer changes much like those of a similar island in the cooler seas, because any small fringing reefs that might be early established on its firm lava points will soon be smothered by the abundant detritus washed down to the shore by torrential streams. Thereafter no reefs can ordinarily be formed so long as the ocean level remains unchanged, as I have shown in a special article (1916a), and as will be further explained when the island of Réunion in the Indian Ocean is described in Chapter X. In the absence of reefs, the

shore will be cut back in cliffs, and the cliffs will retreat indefinitely: the valleys will have hanging mouths in the cliff face. When the ocean sinks in a Glacial epoch and the withdrawing shore lies upon the unconsolidated detritus of the normal embankment, protecting reefs will still, as Daly has pointed out, be unlikely to establish themselves, and part or all of the normal embankment and platform will then be cut away, as on the left or right side of Figure 43. The previously hanging valleys will be at the same time more or less deepened.

FIG. 42—Profiles of a stationary island in the cooler seas.

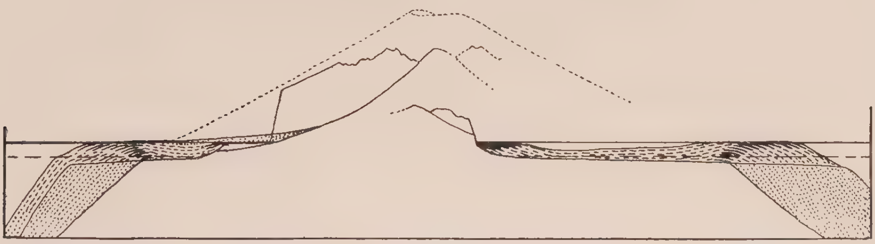


FIG. 43—Profiles of a stationary island in the coral seas, at successive stages of its degradation and abrasion, modified by reef upgrowth.

When the ocean rises and warms again, the most deepened valleys may be partly submerged as short and narrow embayments, in which the downwashed detritus will then be retained. Fringing reefs may grow on the shore, and barrier reefs may grow up from the cut-back edge of the normal platform or perhaps from exposed ledges or from quiescent cobbles on the low-level platform. During later Glacial epochs coral growth may be expected to migrate down and up the exterior face of the first-formed reef, as changes of ocean level take place, and thus protect the central island from further abrasion. Yet if the reefs are near the shore they may in time be smothered by advancing delta detritus, and then abrasion will begin again, even in a non-Glacial epoch. But if the reefs rise from the low-level platform well offshore and enclose a broad lagoon, they may long survive and protect the island. When the central island is so far reduced in size that its yield of detritus is much diminished, any reefs then surviving should persist. If the island is so young that it has experienced only the latest Glacial epoch, its cliffs will still be clearly recognizable today. If it is old enough to have experienced all the

Glacial epochs yet not so old as to have lost a mountainous form, and if its reefs persist, its cliffs, protected by the reefs from the outer waves since they were cut in the first Glacial epoch, will today be weathered back to moderate slopes; but the spurs will still have evenly truncated ends, and the rock-bottom depth of the embayments will be less than the measure of ocean lowering.

Fig. 44—An emerged and dissected barrier reef, R', on a stationary island during the lowered stand of the ocean in a Glacial epoch.

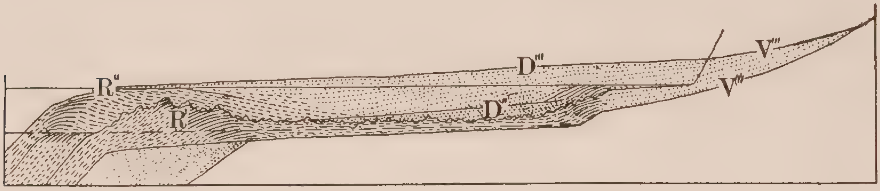


Fig. 45—A new barrier reef, R'', covering a dissected reef, R', on a stationary island, after the Postglacial rise of ocean level.

The reefs of such an island would be emerged during the Glacial epochs following the one of their formation and would be more or less eroded, as in Figure 44; but they would be rebuilt in the next non-Glacial epoch, as in Figure 45. A normal valley, V', Figure 44, that has been eroded before the earliest Glacial epoch experienced by the island, will be deepened, V'', while low-level abrasion in that epoch is cutting back a platform. But in a later Glacial epoch the same valley may have to be aggraded, V''', because its delta, D''', must then be built across the emerged lagoon floor. Hence islands of this kind are not likely to be well embayed.

If a stationary island were of ancient origin, it might have been reduced to low relief with deeply weathered soils in Preglacial time. This would be more probable if fringing reefs of accidental origin were then present, although such an accident is deemed unlikely because of the continual outwash of stream detritus. An island thus conditioned might then be more or less reduced to a low-level platform, Figure 46, *C*. If subdued hills rose on the normal lowland, they might be cliffed on their outer side by normal or by low-level abrasion while the normal valleys between them were deepened by low-level erosion, as Figure 46, *D*. Residual lowlands or cliffed hills of this kind would later constitute the islets of almost-atolls. The inter-islet lagoon area of almost-atolls thus developed must be of less depth than the measure of ocean lowering. It may also be imagined that a residual lowland of the kind just described is so

limited in area and resistance that it would be worn away at normal ocean level by the weak waves of the lagoon; an atoll thus produced would have a shoal in its lagoon center. The only atolls with normally deep lagoons producible on stationary foundations would be those whose worn-down lowlands had been completely truncated by low-level abrasion in the first Glacial epoch; and such atolls ought to be of moderate size.

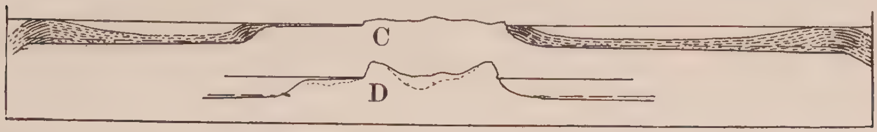


FIG. 46—Profiles of a worn-down stationary island in the coral seas, partly consumed by low-level abrasion.

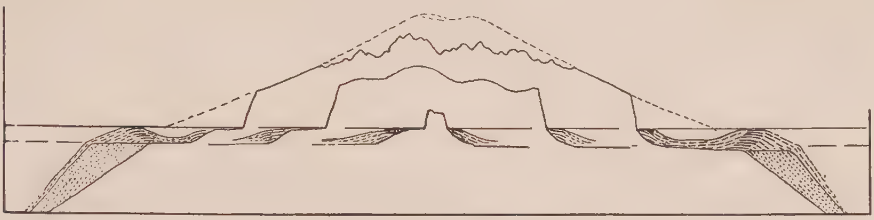


FIG. 47—Profiles of a stationary island in a marginal belt of the coral seas.

STATIONARY ISLANDS IN THE MARGINAL BELTS

A stationary island in a marginal belt of the coral seas may be expected to pass through a series of changes represented in Figure 47. Here, after the preliminary abrasion of a normal platform in Preglacial or Interglacial time, only low-level abrasion will take place subsequently, because only in Glacial epochs will a protecting reef be absent. If the island is young, it may have lost all its normal platform in the last Glacial epoch, and it will then be characterized today by plunging cliffs of moderate height, rising from a low-level platform of moderate breadth; the platform will be somewhat aggraded as a bank and will bear a more or less successful bank barrier reef. If the island is somewhat older, the low-level platform, the work of several Glacial epochs, will be wider; but the reef, the growth of only the last Glacial epoch, will still be relatively narrow. The embankment around such an island will have had a continual increase in width, for it will have gained detritus from the retreating normal platform in Glacial epochs and from the bank reef in Interglacial epochs.

RISING ISLANDS

Rising islands in the cooler seas will be benched around their shores during pauses in elevation, and the benches will later be seen as terraces of unlike breadth and height on the emerged slopes. The lower terraces

will be well preserved; the upper ones may be much dissected by small ravines and obscured by talus. Glacial changes of ocean level will complicate the succession of benches but will not materially alter their character.

Rising islands of good size in the coral seas and also in the marginal belts will ordinarily be reefless, for their emerging shores will continually be cloaked with loose detritus on which reefs can hardly be established. They will therefore be irregularly terraced, much like similar islands in the cooler seas. If it should happen that reef fringes are formed during a pause in emergence, they will be seen after emergence to rest upon the abraded volcanic slope or upon its cloak of detrital deposits but not on a subaerially eroded slope; except that if a reef is formed at normal sea level after the sea has risen from a low-level stand, the surface of abrasion on which it rests will have suffered such a limited measure of low-level subaerial erosion as could have been accomplished while the ocean was lowered.

Subsiding Islands in the Cooler Seas

Subsiding islands in the cooler seas will be attacked by the waves at successive levels nearer and nearer their summits, as in Figure 48. After the first-cut benches are submerged they will be more or less obscured by detritus from the later-cut benches. Glacial changes of ocean level will here again complicate the succession of benches but without significantly affecting their character. Just after an island of this kind is wholly submerged, it might be easily discovered as a small shoal or bank, and de-

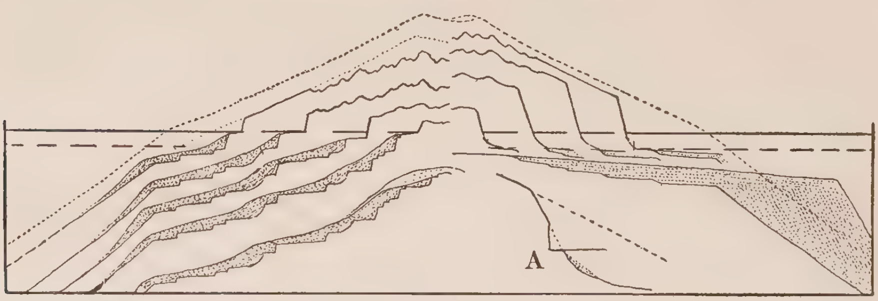


Fig. 48—Profiles of a subsiding island in the cooler seas.

tailed soundings might then detect its larger benches. After deeper submergence its discovery would be more unlikely, and an increased cloaking with pelagic deposits would make its benching hardly detectable.

If subsidence take place rather frequently by sudden downward movements of a considerable measure separated by relatively brief pauses, narrow and nearly flat benches or platforms will be cut at successive levels; the successive profiles of such an island are shown on the left side

of Figure 48. The shore line of such island will ordinarily be most embayed when it is submerged to about half its original height. The eventual disappearance of the island will be due under these conditions more largely to its sinking out of reach of the waves than to its consumption by them. On the other hand, if the subsidence of an island is accomplished by a slow and nearly continuous movement with occasional slight accelerations, inclined platforms will be abraded, and the passage from one platform to the next will be by a curved slope, as in the right half of Figure 48. If the ratio of abrasion to subsidence be large, the original cone will be for the most part destroyed by wave action, the platforms will be broad, and the cliffs at the inner margin of the last-cut platform will be high. Such an island will not have a strongly embayed shore line at any stage of its subsidence.

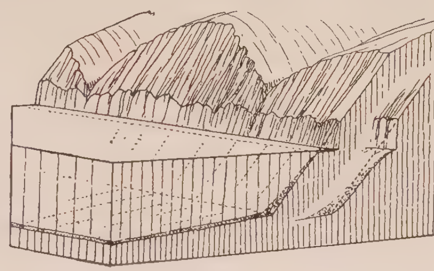


FIG. 49—Diagram illustrating the sine-and-cosine relation of a spur-end bluff and bench.

A matter of detail may be here introduced: Let a cliff be cut back so far that, with increase of platform breadth, it slants back some degrees from the vertical; and let it next be rapidly submerged to about half height. Then a narrow bench backed by an upright wall, Figure 49, will be cut in the slanting cliff face at the level where the waves attack it; and in such case the wall height and the bench breadth will stand closely in the ratio of the sine and the cosine of the cliff-face slant. Hence if a wall and bench with this ratio be found in the face of a slanting, plunging cliff, as seen in Figure 49, the submergence by which the cliff was partly drowned

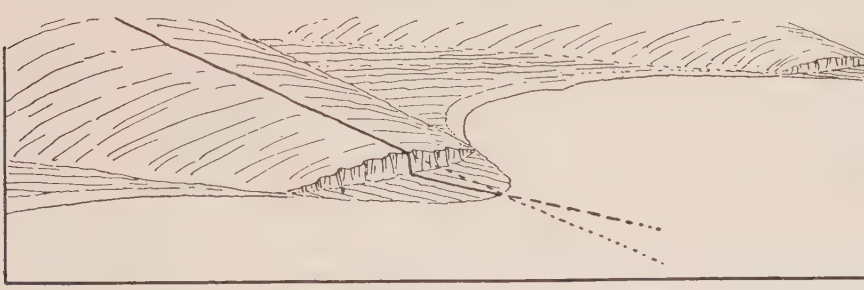


FIG. 50—Wall-and-bench cut in a sloping spur in sine-and-cosine relation.

before the wall-and-bench cutting began must have been rapid and therefore probably due to a quick subsidence of the island rather than to the slower Postglacial rise of the ocean. For if the submergence had been slow, some abrasion of the cliff face would have been accomplished as it sank below sea level; and if a wall and bench be then cut during a pause, as in the inset profile of Figure 49, the wall height will have a greater

ratio to the bench breadth than that of the sine to the cosine of the cliff-face slant above the wall. This principle will be later referred to as the sine-cosine ratio. It applies equally well to a partly submerged spur, as in Figure 50.

Subsiding Islands of the Coral Seas

Subsiding islands in the coral seas will ordinarily be reefless and cliffed during early still-stand pauses, for reasons above explained. But as soon

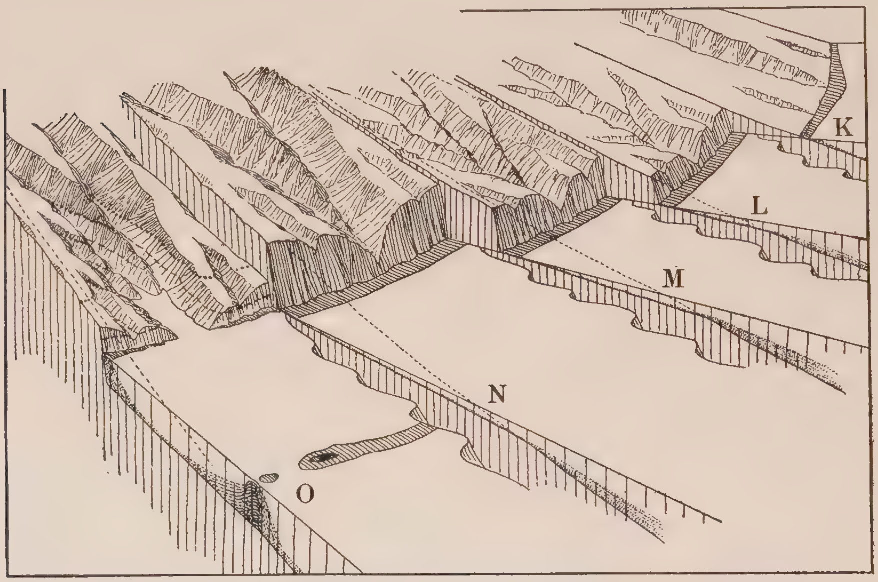


Fig. 51—Diagram showing, in sectors *K*, *L*, *M*, *N*, the abrasion of cliffs on a young, still-standing volcanic island; and, in block *O*, the effects of a moderate subsidence, partly drowning the cliffs, embaying the valleys, and promoting the upgrowth of a barrier reef.

as such an island subsides sufficiently to submerge its cliff-base platform and to cause its cliffs to plunge into clear water—still better if the subsidence suffices to drown the hanging-valley mouths—reefs may be formed either on the cliff face, *C′ R′*, Figure 52, or possibly on offshore ledges or cobbles of the submerged rock platform. If reef upgrowth then accompany further subsidence, later abrasion will ordinarily be prevented. This important inference may be further illustrated by Figure 51. Here a young island, block *K*, is increasingly cliffed, blocks *L*, *M*, *N*, as long as it stands still or subsides very slowly, because the abundant detritus washed down by its steep streams and weathered from its cliff faces forms a sheet of unconsolidated cobbles, gravel, and sand on the cliff-base platform and thus prevents reef establishment. But when subsidence progresses rapidly enough to drown the valley mouths, as in sector *O*, fringing reefs may form on the firm rock of the plunging cliff face, and a barrier may perhaps grow up from the outer part of the offshore plat-

form; or from the detrital embankment, if cobbles and pebbles that were rolled about, previous to subsidence, then rest quietly in the deepened water. The little reef of Walu Bay, at Suva, Fiji, seems to illustrate the latter possibility: it is described in Chapter XV.

It may happen, however, that a somewhat prolonged pause in subsidence or a marked decrease in its rate permits the streams to fill with delta detritus, D''', Figure 45, any lagoon that a barrier reef may have enclosed and then to overwhelm the reef, R'', itself. Thereupon abrasion may set in again and in time attack the island and cut cliffs once more but at a relatively higher level, C'', Figure 52, than before. The larger

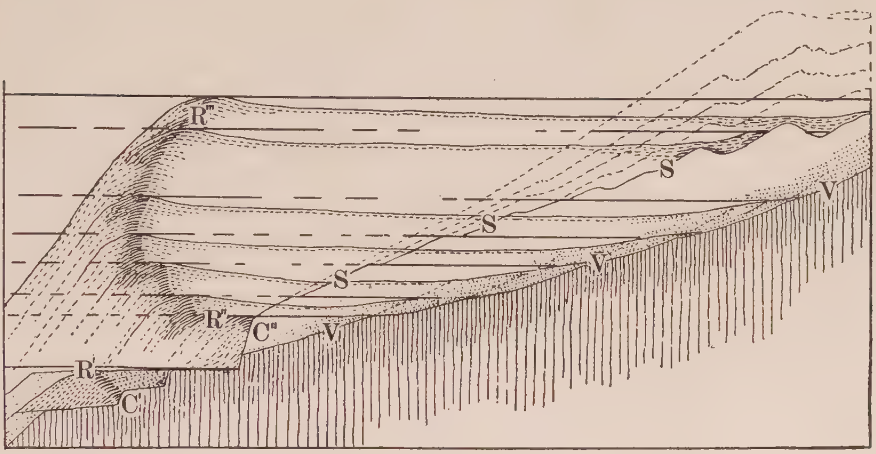


FIG. 52—Ideal section of an upgrowing barrier reef on a subsiding island.

the island, the narrower its first-cut platform, and the slower its subsidence, the better will be the chance of such a happening. But renewed subsidence may in time re-institute reef growth, perhaps on the face of the new cliff, as at C'' R''. Thereafter, the longer both slow subsidence and reef upgrowth continue, the less likely will the reef be again smothered; partly because the lagoon will be widened as the island sinks, partly because the diminished island will supply less detritus with which to fill the widened lagoon. The accumulating lagoon limestones and the intercalated sheets of island detritus will necessarily rest unconformably upon the eroded slopes of the subsiding island.

Brief consideration may be given to the improbable yet possible case of the broad lagoon back of a well offset barrier reef, sector J, Figure 53, being converted into a mature reef plain during a prolonged still-stand pause. The advancing deltas, sectors K, L, reach the reef, sector M, which may thereupon be saved from being smothered and cut away, sector M', by being submerged, sector N; and after this a new reef may grow up, sector O. Imagined examples of this kind are of practical value in the exploration of coral reefs, because they increase the mental

outfit of conceived forms with which actual forms may be compared, and thus sharpen the observation of actual forms. That the production of a mature barrier-reef plain is not an altogether imaginary contingency may be shown by the present condition of the barrier reef on the southeast side of Viti Levu, Fiji, where the delta of Rewa River has almost filled the lagoon. A continuance of delta advance there must inevitably smother the reef, whereupon it will be cut away by the waves. The example of the Rewa delta also serves to show that a ma-

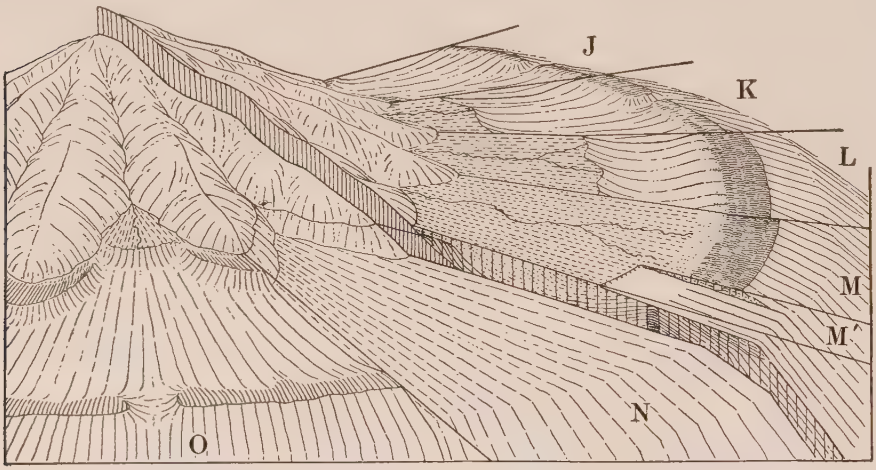


FIG. 53—Sector diagram to illustrate the effects of still-stands alternating with subsidences.

ture reef plain need not be uniformly developed all around a reef-encircled island; it will be first formed wherever island detritus is most abundantly outwashed; and there also the encircling reef will be first smothered. Indeed, if a heavy stream flood carries muddy fresh water out across a narrow and shoaled lagoon to a reef or if the lagoon currents drift sand and silt out, the reef corals may be killed and the reef cut away before the corals are covered and smothered by the advancing delta front.

After the early-cut cliffs of Figure 52 are wholly submerged, the spurs, *S*, *S*, *S*, then more or less rounded by degradational processes, will dip into the lagoon waters with curved, non-cliffed shore lines; and the bays between the spurs will gain in width and inland reach because the valleys will have been more and more enlarged as the island slowly subsides.

It may be recalled that the estimated rock-bottom depth at the mouth of the embayments on certain reef-encircled islands has been said to be greater than the calculated measure of ocean lowering in the Glacial epochs. It may now be explained more fully that the rock-bottom depth of such embayments must be less than the total subsidence by which the embayments were produced; for the original shore line does not lie under the spur-end line, but farther seaward, and at a depth where the slope of

the spurs, *S*, *S*, *S*, meets the fall of the valleys, *V*, *V*, *V*, Figure 52. This is more clearly shown in Figure 54, in which a simple initial shore line, *GDG*, is converted by subsidence into a strongly embayed shore line, *FHF*. The rock-bottom or stream line, *ABCD*, of a submerged valley will have a depth at some point *B*, between bay head and bay mouth that may be roughly inferred by completing the valley cross section, *EBE*, as indicated by the visible slopes of the spurs; but this depth is less than the embaying subsidence: for although *B* will lie below the aggraded bay

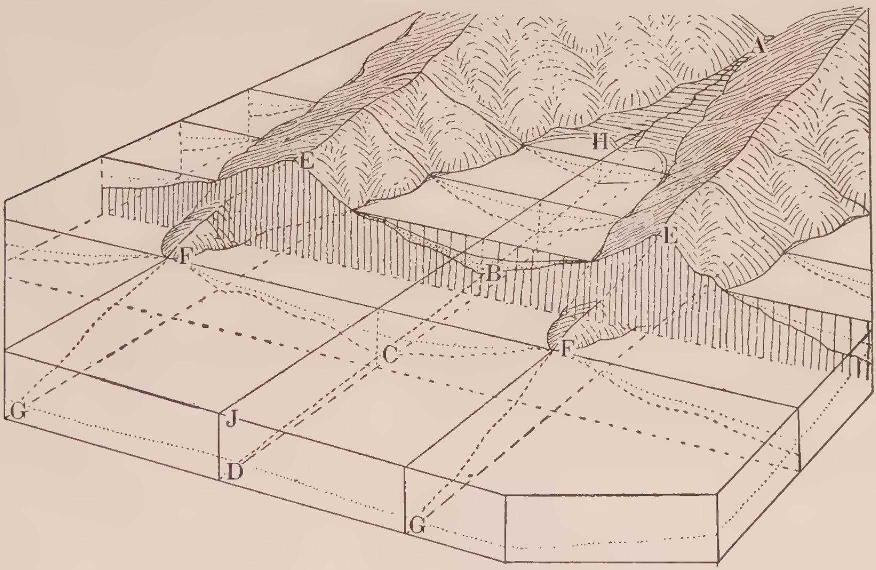


FIG. 54—Block diagram showing true measure of the subsidence, *JD*, that produced the bay, *FAF*.

bottom, it will lie above the level of the sea with respect to which the valley, mouthing at *D*, was eroded.

The Production of Maximum Embayments

In this connection an inquiry may be made as to the measure of subsidence required to produce the maximum embayment of an island shore line. A conical volcanic island will be dissected by consequent streams, so that radial valleys will alternate with radial ridges or spurs. When dissection has reached a mature stage, the spurs will be rounded and the streams will have developed fairly well graded courses of curved descent with a gradually decreasing declivity to the stream mouth. The stream curve, concave upwards, will persist, but with a continually decreasing steepness throughout its length, as the island is further degraded. If a series of contour lines be drawn around such a maturely dissected island, each line will advance around a spur and turn inward at a valley. The question then arises as to the measure of submergence, reckoned in terms of the original height of the island, that will produce the strongest em-

bayment of the island shore line. Before submergence the horizontal recession of a contour as it turns in from spur axis to stream line on a still-standing island will be zero at the stream head and zero at the stream mouth; the contour of greatest recession will lie at some intermediate level, at about a third or a half of the island height. This contour may be called the contour of maximum indenture. The production of a maximum embayment will therefore demand the submergence of the lower third or half of the original island height.

The bay length then developed may be half the radius of the visible spur end measured from the island center; but so great a proportion of bay to spur is seldom seen. If the bay length be a quarter or a third of the spur radius, the submergence should be about a sixth or a fifth of the original height of the island, or a fifth or fourth of the surviving height. As well embayed islands have heights of from 2000 to 5000 feet or more, their subsidence thus roughly estimated may be from 300 to 1000 feet at least. This confirms the estimate of strong subsidence needed for the production of well offset barrier reefs around well embayed islands; it confirms also what has been said regarding the impossibility of producing strongly embayed shore lines on stationary islands by the erosion of valleys with respect to the lowered Glacial ocean and their submergence by the relatively small rise of the Postglacial ocean.

Various Details of Reef Upgrowth

The lowering of the ocean either by crustal movement or by climatic changes in the Glacial epochs will have little effect on the development of a barrier reef as above outlined. There will be no cessation of coral growth, because the steep outer face of the reef, swept clean to cemented reef rock as emergence progresses, will afford a fitting base for corals to grow on. Descending and remounting growth, as if due to a lowering and rising of ocean level caused by crustal movements, is shown four times in the upgrowth of the reef from R'' to R''', Figure 52. In the case of a heavy barrier reef of the kind here drawn, Glacial changes of ocean level, being of late date, would not be expected until the reef had nearly reached its uppermost growth around the subsiding island. So much of the reef as is laid bare when the ocean is lowered will be more or less pitted and removed by solvent erosion, R', Figure 44; but the losses thus occasioned will soon be made good when the ocean rises again, R'', Figure 45. The island valleys, previously embayed and more or less delta-filled, will be in part at least freed of detritus by the low-level erosion of their streams during each Glacial epoch; but, as stream action on an emerged section of a valley at such times will be much the same as before the valley was submerged, the modification produced in the form of the valley will not be marked.

At any stage of these changes submergence may become so rapid that

the barrier reef will be drowned; this is especially likely to happen if moderately rapid subsidence be combined with ocean rise. Then the new shore line will become the seat of a fringing reef of a new generation, from which a new barrier reef will be developed if slower subsidence next follows. When the almost-atoll stage of such a reef is reached, the single original island may be resolved into several much smaller islands or islets, and these islets will have the form of more or less rounded mountain tops. The submerged spaces between the islets may have considerable rock-bottom depths.

If rapid subsidence takes place after the atoll stage is reached, the reef will be drowned. True, if the rapid subsidence be of small amount, the drowning may be only temporary; given time, the reef may grow up to the sea surface again, especially if the depth of the drowning be opportunely diminished by a fall of ocean level. But, if rapid subsidence be of greater amount or if it happen in association with ocean rise, the reef may be so deeply drowned that its upgrowth cannot be resumed. The reef may then be gradually disintegrated while the lagoon floor is more or less aggraded, and the drowned atoll will thus become a rimless bank. If subsidence still continues, the depth of the bank will increase, except in so far as it is aggraded by organic detritus.

Depth of Reef-Enclosed Lagoons

The depth of a barrier-reef or atoll lagoon on a subsiding foundation is not limited by the standard depth of a rock platform of low-level abrasion, as is postulated in the Glacial-control theory; it is determined chiefly by the difference between subsidence and aggradation. But if a shallow lagoon floor is laid bare when the Glacial ocean is lowered, it will be more or less degraded to a standard depth, as I have elsewhere suggested (1923c). It may be here said once again that the presence of the reef by which a lagoon is enclosed demonstrates that any subsidence of the reef foundation which has taken place has not been on the average faster than reef upgrowth. Hence it is not unreasonable to suppose, as long as no accurate quantitative measurements of subsidence and lagoon aggradation are available, that such aggradation is not significantly slower than reef upgrowth. Indeed, in view of the actual exportation of fine sediments, as already noted, lagoon aggradation without such exportation might be fully as fast as reef upgrowth. Certain compensating processes appear to be at work here: If an active subsidence of small amount submerge a reef slightly and deepen its lagoon, the inwash of detritus will be more active and its exportation somewhat less active while the reef is growing up again; thus the deepened lagoon will be rather actively shoaled till a more normal depth is reached. On the other hand, if a stationary period occur, the reef will broaden, sand islands will be built upon its flat, and the inwash of detritus into the lagoon will be checked or stopped; and thus the shoaling of the lagoon will be retarded.

Recurved Upgrowth of Heavy Reefs

Whether a reef grows vertically upward or inclined outward or inclined inward will depend on a variety of factors which I have discussed in a special article (1916b); they are in brief as follows: It must be first recalled that the upgrowth of a reef is necessarily much slower than the upgrowth of corals and other reef-making organisms, because so much of their growth is washed outward to form a submarine talus or is washed inward to build and broaden the reef flat and to aggrade the lagoon floor: some of it is even washed out of the lagoon. The manner of upgrowth must therefore be such as will bring about a balance between the demand of detritus for talus, reef-flat, and lagoon-floor building, and the supply of detritus from the growing reef face. Inasmuch as the breadth of the growing face may be a very small fraction of the total breadth of talus, reef flat, and lagoon floor, the growth of the corals and their associates must be at a much more rapid rate than the growth of the reef as a whole.

A fringing reef will grow horizontally outward in shallow water rather rapidly during a still-stand of a sloping foundation, because in such a case the corals have to supply detritus only for a talus of small depth. If slow subsidence supervenes, more detritus will be demanded not only for a talus of increasing height but also for the construction of a reef flat and the aggradation of a lagoon. So long as these demands are not very great, the reef may grow upward and outward; but with increase of talus length the volume of detritus required to build the talus forward will become so large that an obliquely outgrowing reef may somewhat overhang its talus; it will then be undercut by wave action, and the horizontal component of its growth will be thereby checked. Its upgrowth will thereafter be more nearly vertical; for with more nearly vertical reef upgrowth, the talus will be built outward more slowly, and a smaller volume of detritus will be demanded for its building. As subsidence continues and talus length increases still more, reef upgrowth must incline inward; for if it does not, the reef will come to stand out above the slowly growing talus, and it will then be broken off and cut back by the waves until it does incline inward. Only with an inward upgrowth of the reef can the outward building of the lengthening talus be retarded sufficiently to reduce its growing demand for detritus to equality with the supply. It is for these reasons that the upgrowth of the heavy barrier reef shown in section, *R''*, *R'''*, Figure 52, is represented as recurving from outward to inward upgrowth.

The consequence of such recurved growth will be first to increase the diameter of a reef circuit and later to diminish it. With increase of reef circuit and with the consequent decrease in its rate of curvature as seen in plan, the downslope strip of talus supplied with detritus from a unit of reef-front length becomes more nearly parallel-sided, and the decreased

demand for detritus thus caused partly compensates for the increased demand due to the increased length of the slanting talus strip as subsidence progresses. But with inward upgrowth there will be a shrinking of reef-circuit length and an increase in its rate of curvature; the sides of a talus strip below each unit of reef-front length then become more divergent; and this, with increasing length of talus, calls for a greater supply of detritus for outward talus growth. The growing face of the shrinking reef cannot meet this increasing demand unless its inward upgrowth becomes more nearly parallel to the slant of the talus, so that talus outgrowth shall be retarded. Under such conditions, continued subsidence must result in a continued decrease in the diameter of the reef circuit; and eventually the reef will be reduced to the mere vertex of a great submarine cone. After that, further subsidence, even if not rapid, will extinguish the reef. In confirmation of this sequence of suppositions, it may be stated at once that, in the space between certain larger and recently uplifted reefs in eastern Fiji, several small reefs stand at or a little above sea level, precisely as they should if they had been extinguished before the uplift of neighboring larger reefs brought them up to sea level again. Yet the subsidence which caused their extinction was not rapid enough to drown the neighboring larger reefs. Such reappearing reefs I have called resurgent (1916b).

The foregoing argument suggests also that salients in the plan of a reef will be slowly built outward, because of the small supply of detritus for the downward widening of their talus surface; and conversely that reëntrants will be rapidly filled out. Hence initially irregular fringing reefs should gain more smoothly rounded patterns as they grow up in barriers; and the barriers will eventually become, after much foundation subsidence and reef upgrowth, almost circular atolls. Therefore, if atolls have angular outlines, it may be inferred either that they have not experienced a very great upgrowth or that their angles are the result of submarine downslides of oversteepened talus masses.

Subsiding Islands in the Marginal Belts

A subsiding island in a marginal belt will be attacked by the waves and cut back in cliffs for a time after its eruptive construction is completed; but, when subsidence is well under way and embayments are formed, reef growth will begin, as in the case of similar islands in the coral seas. When a Glacial epoch arrives, the encircling reefs and the shallower parts of the lagoon floors will be cut away and the island itself may be again attacked; but with the coming of an Interglacial epoch, defending reefs will grow up once more, presumably based on a previously cut, low-level platform. Thereafter the subsiding island may be cut back and its detrital embankment built outward in successive Glacial epochs but at relatively higher and higher levels. Today it should show plunging cliffs and offshore

reefs of more or less successful growth over a somewhat aggraded bank. It is manifest that under this explanation a cliffed residual island in the center of an extensive bank, as in Figure 55, does not demand so great an amount of abrasion for its production as if an island originally nearly as large as the bank had stood still while it was cut away; for in the case here supposed much of the original island's volume may have been disposed of by subsidence. Reef upgrowth and lagoon-floor aggradation must here

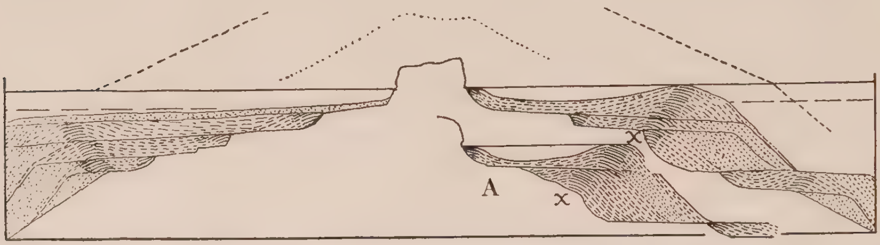


FIG. 55—Profiles of a subsiding island in a marginal belt of the coral seas.

have played a large part in building up the circuminsular terrace-like mass.

Embayments in islands of this class may be either large or small. They will be small or wanting if the island subside slowly and remain reefless and unprotected during a large part of every Glacial epoch, as may be the case if it stand near the polar side of a marginal belt. In such case the recession of the shore cliffs should continually undercut the shortened valleys, and keep them hanging well above lowered sea level. Hence their embayments will be small when normal ocean level is resumed. On the other hand, if the subsidence of an island be more rapid and if it remain reefless during only a small part of each Glacial epoch, as may be the case if it stand near the equatorial side of a marginal belt, large embayments may be produced, provided stream erosion was well advanced before the rapid subsidence began. In the late stage of such subsidence, an island may be reduced to a stellate or skeleton pattern, with moderately cliffed spur ends between broadly rounded, valley-head bays. Evidence of rapid subsidence in such a case might also be found in the unusual depth of the surrounding bank or in the presence of submerged benches in the bank.

It is understandable that, in view of the somewhat lower temperature of the present Postglacial epoch as compared with that of Preglacial and Interglacial times, the reefs of the marginal belt should be less vigorous than those of the coral seas. Also, that in consequence of a delay in the attainment of a temperature sufficiently high for reef growth, the Postglacial reefs might not be established on the outer margin of the circuminsular platforms but on a shallower inner part of the platform, which aggradation in the meantime transforms into a bank. A reef of this kind

would be a bank barrier or, if the central island had been completely removed either by subsidence or by abrasion, a bank atoll. Manifestly, reefs of these kinds will not necessarily grow up in vertical continuation of the preëxistent reefs that have been cut away by low-level abrasion. The new reefs may therefore be properly regarded as independent structures of small thickness, built on platforms in the production of which they took no part. Nevertheless, a marginal-belt barrier reef, intermittently built up and abraded around a subsiding island, may be fairly treated as a single formation, or at least as one composite formation, as long as the upbuilding process produces a fairly continuous structure.

Summary

The chief conclusions of the preceding sections are as follows: Stationary islands in the cooler seas should, if of recent origin, have sea cliffs rising from narrow platforms of normal abrasion. If of earlier origin, they should have higher cliffs rising from broader platforms, around which low-level platforms are to be expected. If of ancient origin, the islands should be completely truncated; the larger ones should have normal platforms rimmed with low-level platforms, while the smaller ones might be wholly reduced to low-level platforms. So far as any cliffed islands survive, they should be but slightly embayed, if embayed at all.

Stationary islands in the coral seas should, if young, be cliffed, slightly embayed, and encircled with narrow reefs. If of earlier origin, their cliffs should be weathered and somewhat dissected, their embayments should be better developed although not of great inward-reaching length so long as the island is mountainous, and their reef-enclosed lagoons might be partly occupied by normal platforms. If of ancient origin, they might be today represented by almost-atolls, in which the surviving islets should be cliffed on the outer side; or by true atolls, in the center of which the surviving part of a normal platform should stand as a shoal, unless the island was small enough for such a platform to be completely cut away by low-level abrasion. The reef flats might have acquired a considerable width.

Stationary islands in the marginal belts should, if they have not been completely cut away, be cliffed; and the cliffs should usually plunge below normal sea level. In so far as such islands survive in good size, they would be of rather massive pattern and moderately embayed or not embayed at all. Instead of having plunging cliffs, the islands may be surrounded by a normal, cliff-backed platform, the outer part of which may be cut back and rimmed by the submarine bluff of a low-level platform. The reefs of Postglacial growth will probably be slender and incomplete novices of the bank-barrier or bank-atoll kind. In all three regions, the expected platforms, either at normal or at low level, will not be directly observable, because they will have been converted into banks by Postglacial aggradation of unknown thickness.

The features of rising islands are so simple that they need not be summarized here.

Subsiding islands in the cooler seas should be cliffed, in so far as they survive; their submarine profiles should be more or less distinctly benched. After their submergence, continued subsidence would lower them to depths where their discovery by sounding would be unlikely. Hence as a rule only the younger subsiding islands of these seas would be known.

Subsiding islands in the coral seas would, if very young, be cliffed and reefless. If somewhat less young, they should be cliffed, moderately embayed, and reef-encircled. If of earlier origin, well embayed with non-cliffed spurs and encircled by barrier reefs of variable breadth enclosing lagoons of ordinary depth. If of ancient origin, they might be represented by almost-atolls with round-topped, non-cliffed islets or by atolls which would memorialize vanished islands.

Subsiding islands in the marginal belts might, if they have subsided slowly and slightly, resemble stationary islands; for they would have plunging cliffs surrounded by a bank of ordinary depth; their reefs would be of the bank-barrier kind. But if they have lately subsided more rapidly, they might be of skeleton outline, rather strongly embayed and with cliffed spur ends; their surrounding banks might be benched at various depths.

It is not to be questioned that the discussion of this chapter is largely speculative, especially in its sections concerning the marginal belts of the coral seas. It is intentionally so. But the more clearly the characteristics of imagined stationary and subsiding islands in the several seas are deduced, the more definitely the characteristics of actual islands and banks in the several seas can be studied. As a justification for these speculative deductions, it may be stated at once that by means of them the islands of the marginal belts will be shown in Chapter VIII to be of a subsiding disposition, and that this interpretation of their behavior will then be seen to have the recommendation of bringing a great number of disconnected facts into a coherent relation with one another. In so far as the interpretation is true, it gives a meaning to the peculiar features of marginal belt islands and to their singular bank reefs that has not been heretofore perceived; and it gives also a quantitative or areal value to the influence of Glacial changes in ocean level and temperature upon the growth of coral reefs, a value that is found to be very different from that assigned to it under the Glacial-control theory. The interpretation is, moreover, fundamentally unlike the interpretations of that theory in that it associates the influence of Glacial changes of ocean level and temperature with subsiding instead of with stationary islands; but in justice to the inventor of that theory it is a pleasure to state that my own understanding of the possible entrance of Glacial influences into the coral reef problem was wholly derived from his discussions of them.

It will be later shown that certain banks in the marginal belts are of so

large a size as to demand a considerable lapse of geological time for their production by the combined action of reef upgrowth and lagoon-floor aggradation on the one hand and of low-level abrasion on the other; and this would seem to indicate that barrier reefs had been well developed there in Preglacial time. Thus countenance is given to the belief that the atolls of the coral seas also were probably represented by atolls or by barrier reefs in Preglacial time; and this is another respect in which the present interpretation differs from the Glacial-control theory.

PART II

THE FACTS OF THE CORAL REEF PROBLEM

CHAPTER VII

THE ISLANDS AND BANKS OF THE COOLER SEAS

Introductory Paragraphs

In the discussion of a group of unfamiliar facts, for the explanation of which no satisfactory theory has been announced, it would be advisable to present the facts at the outset and, after they had been sufficiently described, classed, and generalized, to advance whatever theory seems best to account for them and then to measure the value of that theory in comparison with less successful theories. But in the discussion of a group of facts which have been long familiar and for which various competing theories have been proposed, it has seemed desirable to present, after an introductory summary of the facts, first, an exposition of the several theories with particular regard to their assumed postulates and their deduced consequences, in order that preliminary tests of their value may be made; and finally, carrying forward the more successful of the competitors, to proceed to a critical review of the whole ocean of facts, with the object of making if possible a more critical decision as to which theory best explains them all.

In accordance with this plan of procedure, all the better-known coral reef theories have been analyzed and given a preparatory evaluation in Part I of this volume, with the result of finding only two, Darwin's theory of upgrowing reefs on intermittently subsiding foundations and Daly's Glacial-control theory, worthy of further examination. At the same time, while a decided preference for Darwin's has been developed because of its success in meeting preliminary tests, it has also been found that a modification of that theory made by combining with it a leading element of Daly's theory—namely, the influence of the Glacial period in changing the level and the temperature of the ocean—is better than either theory alone. It is therefore chiefly Darwin's theory thus modified that needs further scrutiny, and for this purpose the remainder of the volume will be devoted to setting forth a large array of facts with which the more detailed consequences of the modified theory may be confronted.

Let it be borne in mind that, while coral reefs react upon their surroundings as they grow, they are chiefly the consequences rather than the determinants of their environment. The growth of a coral reef does not ordain that the island encircled by the reef shall rise, stand still, or sink; it

is the rise, still-stand, or sinking of the island itself, as determined by the action of deep-seated telluric forces, which in turn determines the opportunity that coral reefs shall have for growing upon its shores. Hence coral reefs must be treated as items in the geological history of their areas; and that history must include a due consideration of the processes of volcanic eruption, land sculpture, and sea-floor deposition, as well as of the changes of island and of ocean level, along with the processes of reef growth.

In the present chapter, certain islands and banks of the cooler seas will be first examined, with the object of learning how far they support the view, above outlined, that pelagic islands are generally unstable with a tendency to subside. The islands, banks, and reefs of the marginal belts of the coral seas will be examined in the next chapter in more detail, in order to discover how far they differ from the islands and banks of the cooler seas, from which they are separated only by a climatic boundary, and in order also to prepare the way for recognizing the contrast between the marginal-belt islands, banks, and reefs, where reef growth is believed to have been intermittent, and the islands, banks, and reefs of the true coral seas, where reef growth is believed to have been continuous. The provisional assumption that the peculiarly characterized marginal belts of the coral seas really exist will be justified if the expected features of islands and reefs in those belts are actually found. Finally, the islands, reefs, and banks of the coral seas, as well as the reefs and shelves of continental coasts in those seas, will be taken up in several chapters, following an order suggested by an expanded development of Darwin's theory, as will be detailed when those chapters are reached. My own observations on certain islands in the Pacific will be as a rule presented more at length than abstracts of observations by others, largely because the descriptions of reef-encircled islands in books of travel and exploration often fail to include significant items. It may be noted that in Polynesian names every vowel is sounded separately: thus Kaala and Koolau in Oahu have three and four syllables; Papeete in Tahiti is a four-syllable name.

Itinerary of My Pacific Voyage of 1914

In order that the reader may more readily distinguish between accounts of islands based on my own observations and accounts abstracted from articles by other observers, the following itinerary of my Pacific voyage of 1914 is here inserted. Cambridge, Massachusetts, was left on January 31, and after several stops on the way San Francisco was reached on February 9, whence the steamer *Wilhelmina* of the Matson line, sailing February 11, carried me to Honolulu, Oahu, on February 17; a week was then given to the elevated coralliferous limestones of that island. The fine steamer *Niagara* of the Canadian-Australasian line, running between Vancouver and Sydney, took me from Honolulu, February 25, to Suva, on the chief Fijian island, Viti Levu, March 6. Seven weeks were spent in visiting

eighteen Fiji islands, including Ovalau, Mango, Thithia, Vanua Mbalava, Taveuni, Rambi, and Vanua Levu, which were reached on a trading steamer, as well as Makongai, Wakaya, Kandavu, Ono, Nairai, Matuku, Ngau, Totoya, Moala, and Mbengha, which were reached by sailboats. Base-down cumulus clouds (Fig. 56) were frequently seen on these cruises in the trade-wind belt. During my stay many kind attentions were shown me by His Excellency, the Governor of the Islands, Sir Bickham

FIG. 56—Sketch of trade-wind clouds, showing the base-down distant clouds, below the ocean horizon, in proof of the rotundity of the earth; looking north from the north coast of Vanua Levu.

Escott, K.C.M.G., as well as by various other officials and a number of residents.

On May 1 Suva was left on the *Makura*, also of the Canadian-Australasian line, and on May 5 arrival was made at Auckland, New Zealand. A month was spent there on North and South Islands, in making visits and excursions, for which free transportation was most generously given me on all railways, and excellent personal guidance was provided by the geologists of the colleges at Auckland, Wellington, Christchurch, and Dunedin. Departure was made from Wellington, June 5, on the *Moeraki* of the Union Steamship Company of New Zealand, and Sydney, Australia, was reached on June 9. Pleasant acquaintance was there made, through introduction by my most attentive friend, Mr E. C. Andrews of the Department of Mines of New South Wales, with a number of members in other governmental bureaus. The French steamer *Néra* of the Messageries Maritimes, sailing thence on June 12, carried me to Nouméa, New Caledonia, on June 15; the greater part of a month was well used in making a circuit of that long island and in visiting the three Loyalty Islands to the north on trading steamers. A final week was spent in a cruise around the southeastern end of the island in a small sailboat under the pilotage of its owner, M. Cané, who, from his acquaintance with the natives and their very guttural language, as well as with all the headlands and harbors of the coast, proved to be a most helpful guide. The courteous attentions of His Excellency the Governor, M. Auguste Brunet, and of several residents of Nouméa were also of much assistance. A short

trip was then made in company with Mr. E. C. Andrews on the *Pacifique* of the Messageries Maritimes, which brought him from Sydney and on which we proceeded northward from Nouméa on July 18 to the New Hebrides, with stops at the islands of Efate, Epi, Ambrym, Malekula, and Espiritu Santo; we returned southward, touching at Nouméa on July 27, and continued to Sydney, where we arrived July 31 and had our first news of the outbreak of the World War from the pilot at the entrance to Sydney harbor.

The greater part of August was given to the meetings of the British Association for the Advancement of Science in Adelaide, Melbourne, and Sydney. Time was then unexpectedly found for a journey northward by rail, August 27 and 28, and by steamboat, August 29, as far as Cairns, September 1 and 2, on the Queensland coast, whereby opportunity was afforded me of seeing a long stretch of the shore line inside of the Great Barrier Reef and of visiting one of the reef islands. After a return to Sydney on September 10, that beautiful city was left on the 11th, and the return voyage to San Francisco then begun was accomplished on three steamers of the Union Steamship Company: the *Manuka* carried me to Wellington, New Zealand, September 15; from Wellington the *Moana*, sailing on the 17th and touching at Rarotonga in the Cook group on the 22nd, conveyed me to Papeete, Tahiti, the chief island of the Society group, on the 24th, two days after that quiet little French colonial capital had suffered the excitement of a brief bombardment by the German cruisers *Scharnhorst* and *Gneisenau*, then on their way from China to the coast of Chile. Four weeks were allotted to that superb island and five others, Moorea, Huaheine, Raiatea, Tahaa, and Borabora, which were reached by launches. These visits were facilitated by letters of recommendation kindly furnished me by His Excellency the Governor, M. W. Fawtier. Sailing from Papeete on October 23, a placid voyage on the *Marama* brought me to San Francisco on November 5, whence a rapid run was made on overland trains; Boston was reached on November 10. No accidents or delays happened; the entire voyage was made "on time" and for the most part in comfort.

Object of the Present Chapter

Attention will be directed in the present chapter chiefly to the form of certain islands in the cooler seas as determined by eruption, erosion, and abrasion, both normal and low-level, as well as to any changes of attitude apparently suffered by the islands. The rate of cliff recession by unhindered strong-wave abrasion will be shown to be more rapid than that of valley deepening by island streams and much more rapid than that of valley widening by the weather. This conclusion has already been used and will later be used again in interpreting the features of unprotected and of reef-protected islands in the coral seas. Shallow banks, from 5 to 20

miles in diameter, will be particularly searched for, because they should occur if old, stable islands have been completely truncated by normal or low-level abrasion. The depths of circuminsular banks will be examined in order to determine if they bear the marks of low-level as well as of normal abrasion.

The Cooler Seas of the North Pacific.

The review of these cooler seas will be begun with islands in the western part of the North Pacific, where they are most numerous. Two island ranges, one forming the Izu-Bonin chain south of Japan, the other, the Osumi-Riukiu curve southwest of Japan, are so situated that they cross the marginal belt from the cooler to the coral seas and thus exhibit unlike features of special interest. Only the islands outside of the marginal belt are here examined.

Fig. 57—Submarine contours for a bank south of Oshima, Japan.

The Izu Islands

The Izu and the Bonin groups, with a number of smaller intermediate islands, constitute a long chain extending southward from central Japan; only the first-named group and the smaller intermediate islands stand in the cooler sea. The Izu Islands are all shown on HO chart 5301. They include four volcanic islands. The largest and northernmost is Oshima, 8 by 5 miles, 2473 feet high; it is an active, undissected volcano, moderately cliffed around the shore. Three others of small size, more or less cliffed, rise from a single bank, 33 by 6 miles across, with a marginal depth of 60 or 70 fathoms and a rapid descent to deeper water. Several other banks are charted near by; one, 9 miles in diameter, has a central depth of 45 fathoms and a marginal depth of 70 fathoms, as in Figure 57. In this figure, and others of the same kind, the 50-fathom contour is a heavy line; the 100-fathom contour is in part dotted: a scale of miles is given by marks on the margin. The islands between the Izu and Bonin groups are six in number, HO 5257, 5301; they are volcanic cones of small size, less or more dissected and cliffed according to their age: thus Hachijo is a volcanic doublet, measuring 7 by 4 miles; a dissected and cliffed cone on the southeast rises 2298 feet; a less dissected cone on the northwest, 2812 feet high, has lower and more ragged cliffs; a bank of small width adjoins the younger cone, widening to 6 miles off the older cone and having there a marginal depth of 70 fathoms.

Farther south are the ragged Bayonnaise Rocks, 30 feet high, over a bank with near-by depths of 200 or 300 fathoms; this suggests strong abrasion and moderate subsidence. Then follow two remarkable stacks, or volcanic residuals of columnar form: Sumisu-shima, or Smith Island (Fig 58) and Sofu Gan, or Lot's Wife (Fig. 58). The first, 31½° N, 140° E, consists of two pinnacles, of which the larger one has a smaller sea-level diameter than its height of 445 feet; soundings of 147 and 306 fathoms are charted within three miles; others at about double that distance are 461, 349, 578, 513, 431, 388, and 454 fathoms. The other stack, 30° N, 140½°

FIG. 58—Sofu Gan or Lot's Wife (left), Sumisu-Shima or Smith Island (right), abraded stacks in the Izu Islands, Japan, outlined from HO 5257.

E, also has a smaller sea-level diameter than its height of 326 feet; the only near-by soundings are 105 and 110 fathoms two miles away, and 918, 886, 704, 359, 667, and 672 about four miles away. This stack is at least a century and a third old, as it was first reported, according to a publication of the U. S. Hydrographic Office (1871, pp. 27, 32), in 1788; hence it cannot be an extruded spine, like that of Mt. Pelée, as Powers has suggested for certain other tower-like islands (1916); for in that case it should long ago have disappeared. Both these stacks are therefore regarded as representing the penultimate stage in the abrasion of a volcanic island; the depths near them suggest, though they do not fully demonstrate, subsidence during or after abrasion. Tori, or Ponafidin, HO 5257, 1½ miles in diameter, 1268 feet high, is a cliffed volcanic residual standing between the two stacks just described; it is surrounded by a narrow bank with a marginal depth of 70 fathoms. The recurrence of 70 fathoms as a bank-margin depth suggests low-level abrasion unmodified by subsidence or later aggradation, or abrasion and subsidence if aggradation of significant amount has followed abrasion.

The Broad North Pacific

The rarity of islands and banks in the vast central oceanic area of the North Pacific cooler seas is truly remarkable. Omitting certain islands close to the American and Asiatic coasts and also the northwestern islands and banks of the Hawaiian chain, which will be described in Chapter VIII as belonging in the North Pacific marginal belt, the whole breadth of the ocean between latitudes 35° and 50° N has only one island, Reed Rocks, 37½° N, 137½° W, of small size with an adjoining shoal of undetermined

extent; and only two banks of small size, Mellish, 34½° N, 178° E, with a single sounding of 64 fathoms, and an unnamed bank, 30° N, 177½° E, with no recorded soundings. It is of course eminently possible that many banks, small and large, may exist in the North Pacific as yet undiscovered, for no soundings are recorded over wide areas; but in view of the considerable number of shallow banks that have been discovered in or adjoining the coral seas, the failure to discover other banks than the two above noted in the broad cooler seas of the North Pacific strongly suggests that no good-sized shallow banks, such as would result from the truncation of stable islands 10 or 20 miles in diameter, exist there. This suggestion is the more probable because banks resulting from the complete truncation of stationary islands would be more easily found, by reason of being larger and of lying at a moderate depth, than banks representing the small summits of benched and subsided islands of the same initial size.

Three submarine cones rise from the deep ocean floor between San Francisco and Hawaii to depths of 1265, 404, and 976 fathoms; they were discovered by the somewhat detailed soundings made in connection with laying a cable (U. S. Congress . . . survey for . . . cable . . . 1892). Unless still more detailed soundings show that these submarine cones bear marks of subaerial erosion and littoral abrasion near their tops, in which case submergence from a former island existence would be indicated, they may be regarded as young volcanoes that were never built up to sea level.

The Cooler Seas of the Eastern Pacific

In consequence of the equatorward flow of the great Humboldt Current of cool water off the west coast of South America and of a smaller equatorward current along the west coast of Central America—these currents being perpetual consequences of the earth's persistent eastward rotation and of the strong sunshine it receives in the torrid zone—the reefless cooler seas of the North and South Pacific appear to be connected by a relatively narrow and similarly reefless cross-equator belt in the easternmost Pacific. The narrowness of this belt is best indicated by the small, sea-level almost-atoll of Clipperton Rock, an easternmost outpost of the Pacific coral seas, about 600 miles from the coast of Mexico, 10° N, 109° W, HO 1680, which will be described in Chapter XIV. There are no islands in the corresponding area south of the equator.

The Galápagos Islands

This group, HO 1798, 1801, consisting mostly of young volcanic islands, stands close to the equator, about 600 miles from the coast of South America. Five of the islands are of good size; the largest, Isabella, being over ten miles in curved length; five are of small size; and there are many smaller ones. They have been described by Darwin (1844), Wolf (1895), Baur (1891, 1897), Agassiz (1892), McBride (1918), and others, most of the de-

scription being written in the interests of biological science. According to Darwin, who estimated the number of craters at 2000, the island profiles are generally tame; the loftiest summit is 4000 feet high; the shores are more or less cliffed; some of the smaller islands are reduced to stacks; Banks cove was taken to be a breached tuff crater. Culpepper, 850 feet high, and Wenham, 830 feet high, 100 miles northwest of the others, appear on the charts to be cliffed residuals of small size. Agassiz described Indefatigable Island as having "innumerable spits, composed of huge lava blocks running into the sea and separated by small coral rock beaches"; similar features were noted on Chatham, Charles, and Duncan islands; there are no coral reefs, "nothing but isolated patches of reef-building corals." The absence of reefs, which Dana had accounted for by the low water temperature, was ascribed by Agassiz to the "immense amount of silt which is brought down the hill and mountain sides every rainy season, and which simply covers the floor of the ocean to a very considerable distance from the land" (1892, pp. 64, 70). It may, however, be questioned whether, in the very immature and beachless stage of some of the islands, the force of the waves is not sufficient to strip the silt from the shores, especially from the more salient rocky headlands, and whether the absence of fringing reefs there is not due, as Dana thought, to low water temperature. In view of the feeble growth of corals, these islands may perhaps belong on the outer edge of the marginal belt rather than in the cooler seas of the Pacific.

Islands Near the American Coast

Several islands rise in the eastern Pacific not far from the American coast, and to the south of the broad blank area above reviewed: Guadalupe, 160 miles southwest of the head of Lower California, HO 1681, 20 by 6 miles, 4500 feet high, has lofty cliffs but is without a corresponding shallow platform; near-by soundings on the west range from 25 to 226 fathoms. A well illustrated general account of this island has been prepared by Hanna and Anthony (1923). The Alijos Rocks, 150 miles off the middle of Lower California, HO 1687, are a group of small summits, 150 feet or less across and 112 feet in greatest height; one sounding of 36 fathoms is given ⅔ mile northwest. The small Revilla Gigedo Islands, 260 miles south of the end of Lower California, HO 1687, 622, are four in number; they are all cliffed and are surrounded by imperfectly charted banks.

Two small islands southwest of the Gulf of Panama remain to be described: Cocos Island, 5½° N, 87° W, HO 1685, is 3½ miles in diameter and 2788 feet high; several small islands stand near by. Stewart states that, except for two bays, "the shore is made up of tall cliffs, some of which must be a thousand or more feet in height, over the tops of which numerous waterfalls come tumbling down into the sea. . . . The sides of the mountain rise abruptly to a cone. . . . Alternating ridges and deep canyons cover the mountain sides" (1912, 376, 377). No near-by

FIG. 59—Banks Peninsula, a compound volcanic cone, maturely dissected, strongly cliffed, and well embayed by subsidence; east coast of South Island, New Zealand; HO 3344.

soundings are charted. Malpelo Island, 4° N, 82° W, HO 1685, is figured but not described by Agassiz (1892, Pl. 14); it is strongly cliffed. No soundings are charted south of the island, but on the north a good number of soundings show the presence of a bank about a mile wide, with a marginal depth of 60 fathoms.

The Cooler Seas of the South Pacific

The cooler seas of the South Pacific, like those of the North Pacific, present great expanses without islands or soundings. The few islands there occurring are as follows: Seven islands, and a larger number of islets, HO 2003, 2029, stand south of New Zealand; they are in part composed of continental rocks. Some of them have been glaciated, most of them

are cliffed, some are embayed. The banks around them are imperfectly sounded, but in so far as shown the banks seem to be of normal depth, as if they had been aggraded after any low-level abrasion that they have suffered. Macauley, HO 2001, in the Kermadec group, 100 miles south of Raoul, which will be described under the marginal belt, is a mile and a quarter in diameter and 780 feet high, with cliffed, non-embayed shores; a few shallow soundings up to 32 fathoms are charted close by. Curtis,

Fig. 60—Akaroa Harbor, a drowned valley on the southeast side of Banks Peninsula, New Zealand. (Drawn by C. A. Cotton of Wellington, New Zealand.)

HO 2001, still farther south, is half a mile in diameter with cliffed shores and a few soundings to 40 fathoms not far offshore. L'Espérance, a small cliffed rock 230 feet high, and Havre rock, awash, lie still farther south in latitude 31°. Half a degree beyond is Star of Bengal bank, 15 by 5 miles, on which the least depth found in several crossings is 110 fathoms, although an earlier report said the bank was visible from the surface. Additional soundings hereabouts are to be desired, as the few that are recorded do not suffice to define the dimensions or marginal depths of the banks: but the depth suggests subsidence.

A vast extent of blank ocean then stretches eastward, until four relatively young volcanic islands, all shown on HO 1267 and all more or less cliffed, are encountered off the coast of Chile: Juan Fernandez, 12 by 3 miles, 3040 feet high, with but few near-by soundings; Mas-a-fuera, 5 by 7 miles, 6562 feet high, also with but few near-by soundings; San Ambrosio, 1 by 2 miles, 1570 feet high; a bank with soundings from 75 to 90 fathoms extends 3 or 4 miles to the south but is narrow on the north; San Felix, 1 by 1½ miles, 248 feet high, also with a bank vaguely defined extending 2 miles north and 3 miles south. The depth of the San Ambrosio bank suggests subsidence.

Banks Peninsula, New Zealand

A section may be here devoted to Banks Peninsula, HO 3344 (Fig. 59), a mountainous mass 30 by 18 miles, 3012 feet high, on the eastern coast

of South Island, New Zealand. It consists of two volcanic cones closely welded together and much dissected by radial consequent valleys. A good description of it has been published by Speight (1916), in whose company I had a fine view of its western part in 1914. Captain Cook mistook it for an island when he discovered it in 1770, and an island it presumably was originally, until transformed into a peninsula by the forward growth of the Canterbury Plains, largely composed of outwashed Glacial gravels and sands. In spite of being thus closely associated with a large con-

FIG. 61—Port Lyttleton, a drowned valley in the

tinental island, the peninsula may be described in association with oceanic volcanoes as a typical example of a maturely cliffed and dissected volcanic island, now well embayed by subsidence. If the embayments were somewhat longer, it would have a pronouncedly stellate outline; but as it stands it is far better embayed than any other volcanic mass in the cooler seas.

All the numerous radial valleys, except those directed toward Canterbury Plains on the west, are entered by the sea. The two largest bays, each 11 miles in length, are Akaroa Harbor (Fig. 60), which opens southward from the southeastern volcanic center, and Lyttleton Harbor (Fig. 61), which opens northeastward from the northwestern center. All the inter-bay spur ends, except those which descend westward to the plains, end in plunging cliffs (Fig. 62), and some of the cliffs still rise 400 or 500 feet above sea level. Although some steepening of the visible faces of the cliffs has presumably been produced by a short period of wave work at present sea level, it must be supposed that the cliff cutting was chiefly accomplished during a much longer period of greater emergence, while the now-embayed valleys were in process of erosion; and it may be confidently believed that at that time most of the valleys mouthed somewhat above sea level in hanging fashion, although their mouths are

now depressed below sea level. This belief is based on the general principle that strong-wave abrasion is more energetic than short-stream erosion. The partial submergence of the dissected mass is believed to have been caused by subsidence, because the submerged valleys are too maturely opened to have been eroded only during the Glacial epochs of lowered ocean level. And the subsidence must have been relatively rapid after the dissection of the mountain mass by its radial consequent

western part of Banks Peninsula, New Zealand.

valleys was well advanced; for, had it been slow, the recession of the cliffs would probably have continued to undercut the valleys, thus preventing the formation of long embayments, in spite of subsidence.

The amount of subsidence that has taken place since the valleys of the peninsula were eroded cannot be safely determined by the present depth of even the largest embayments, which is only 10 or 15 fathoms; for the rock bottom of the drowned valleys is now buried beneath an unknown thickness of sediments. The larger-scale charts, BA 1999 and 1575, give depths of 10 fathoms on the north and of 20 fathoms on the southeast, not far outside the cliffed spur ends. A bank gradually deepening to 50 fathoms extends 10 miles eastward. Speight does not give special attention to the original attitude of the peninsula, but he records the discovery of layers of peat at various levels down to 700 feet in artesian wells in the low-lying plain to the west; and he adds that, as the peat layers were found as far down as the borings reached, they may occur at still greater depths and thus indicate a still greater subsidence (1916, p. 385). Yet, in spite of this strong subsidence at a rate rapid enough to produce pronounced embayments, the bank that extends eastward from the peninsula appears to have its margin rather closely in adjustment with the bank-making processes of present ocean level. Another district of strong sub-

mergence, evidently due to subsidence, in this New Zealand region is seen in the elaborately embayed mountains of normal dissection at the northern end of South Island, HO 3386, 3387; their exterior headlands, of which I had a view from a passing steamer, are well cliffed; the inner shore lines are extraordinarily intricate.

While still in active growth the volcanic mass of Banks Peninsula presumably resembled the vigorous young cone of Mt. Egmont, HO 3341, 3342, on the west coast of North Island, New Zealand; it is 8260 feet high,

FIG. 62—Plunging spur-end cliffs on the north side of Banks Peninsula, New Zealand.

little dissected, with a simple and regular shore line little cliffed. At an early stage of its erosion and abrasion, the Banks volcano probably had the form of Tristan da Cunha; and when it was further eroded and abraded, but not submerged, it must have resembled the present form of the cliff-rimmed and non-embayed volcanic island of St. Helena, which, with Tristan da Cunha, will be described below. Conversely, this embayed peninsula may be taken as illustrating the form that St. Helena would have if it were submerged from 700 to 1000 feet. Although this fine example of a sub-stellate volcanic mass cannot be taken to prove that oceanic islands are unstable, it may be accepted as illustrating the form that certain dissected and cliffed volcanic islands in the cooler seas would have if, being unstable, they were submerged so greatly and so rapidly as to drown the valley mouths which now hang above sea level in their cliff faces.

The Cooler Seas of the South Indian Ocean

The charts of these seas exhibit, in striking contrast to the numerous and large banks charted in the coral seas of the same ocean, only one small bank: Slot Van Capelle, 37° S, 42° E, 62 fathoms, of undefined size. But in contrast with the vast blank areas of the North and South Pacific cooler seas, several young volcanic islands are found here, more or less cut away by the sea waves. Two of these, New Amsterdam and St. Paul, lie southeast of Madagascar, BA 1921; the first, 5 by 4 miles, 2760 feet high, is a single cone little dissected but with high cliffs bordered by an imperfectly sounded bank over a mile wide; the second, 3 by 1½ miles, 862 feet high, is a young cone with a fine caldera; the southeastern

side of the cone has apparently been downfaulted; the shore is cliffed and fronted with a bank 1 or 2 miles wide without sufficient soundings to determine its extent or marginal depth. These two islands have been well described by Hochstetter (1864–66), Vélain (1878; 1893), and Chun (1900, pp. 269, 278). Marion, Prince Edward, the Crozets, Heard, and some other far-southern islands, all on BA 802, are strongly cliffed; but so few soundings are charted around them that their expectable banks are not defined. The *Challenger* report states, for the Crozets, that "from all sides of the precipitous black cliffs, cataracts fall over into the sea" (1885, p. 321), thus confirming the general rule that the retrogressive abrasion of small islands is faster than the downward erosion of their short streams. Penguin Island in this region is described as "a solitary basaltic islet, which rises in castellated pinnacles 900 or 1000 feet above the level of the sea." Kerguelenland, BA 2398, 30 miles across, has been glaciated and is therefore much embayed; shoals, deepening to 60 or 80 fathoms, extend 10 miles north and 20 miles northeast.

The southern part of Madagascar enters the cooler seas; its middle is crossed by the marginal belt of the Indian Ocean; its greater northern part is included in the coral seas. The physical features of its coast have been so imperfectly described that we cannot yet learn all that they probably teach. Its southern extremity, described by Decary (1920), appears to be a coastal plain resting on crystalline rocks; it is cut back in an almost rectilinear cliff from 250 to 350 feet in height over an east-west length of 90 miles; the crystalline rocks are exposed along the cliff base beneath their stratified cover.

The Cooler Seas of the Atlantic Ocean

The Atlantic Ocean differs markedly from the Pacific in having only a small part of its western torrid area occupied by islands on which reef-building corals are found. The cooler seas of temperate latitudes here stretch across nearly the whole width of the ocean at the equator, and only near the Brazilian coast are coral reefs encountered. The little bank-atoll of the Rocas, not far east of that coast, is the only island of its kind in the equatorial Atlantic; an account of it will be given in the next chapter. It is possible, however, that the absence of reefs on such islets as St. Pauls Rocks, near the equator in the mid-Atlantic, is not due so much to the insufficient warmth of the ocean waters there prevailing at present, as to the lack of a Postglacial supply of coral larvae; for the strong ocean current that flows past those islets comes from the cooler seas of the South and North Atlantic, where corals are altogether wanting. By good fortune the deficiency of open-ocean islands in the cooler seas of the Pacific is not repeated here; volcanic islands are not only numerous in the Atlantis region west of the Iberian Peninsula and northern Africa,

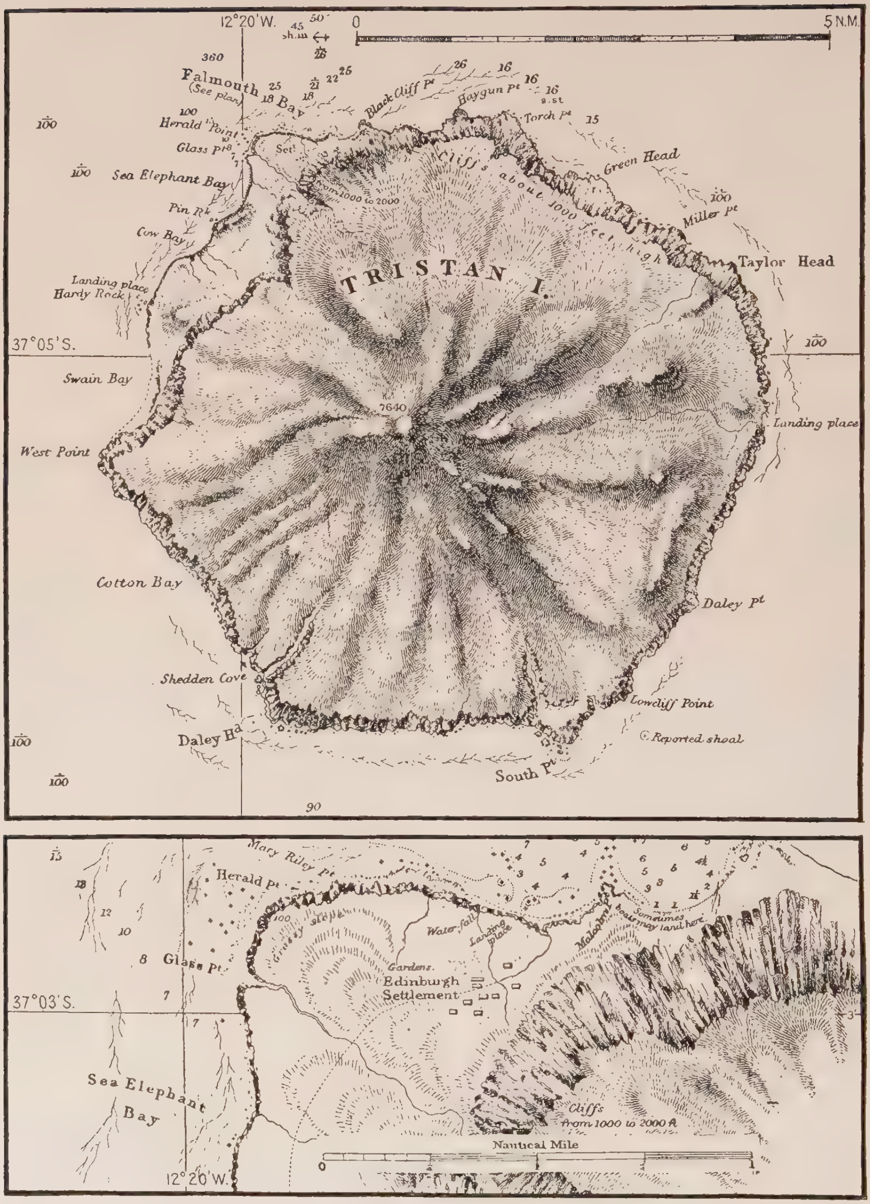


FIG. 63—Above: the cliffed volcanic island of Tristan da Cunha in the South Atlantic. Below: part of the emerged cliff-base platform on the northwest side of the island; HO 3902.

but many of them are well charted with numerous offshore soundings, and the geological history of a number of them has been studied in some detail, from which it appears that several of them are distinctly unstable, but with a tendency to rise rather than to sink. They will be here considered after the few islands in the South Atlantic are described.

Far-Southern Islands and Banks

The Falkland Islands, HO 617, 2451, 2452, of continental origin, are greatly embayed and are surrounded by extensive banks with widths of 10, 20, or 30 miles and depths down to 80 fathoms. Both the islands and the banks appear to be austral counterparts of Newfoundland and its banks; they are therefore irrelevant to our problem. A record on HO chart

FIG. 64—View of Tristan da Cunha, from the "Challenger" Narrative.

1132 states that "an extensive bank with less than 25 fathoms of water is reported to exist between latitudes 45° and 49° South and longitudes 27° and 35° West": the origin of this great bank, which would appear to cover some 50,000 square miles, is wholly unknown.

Among the younger volcanic cones of the Atlantic, none give more striking illustration of strong abrasion than Tristan da Cunha, HO 3902 (Fig. 63), 6 by 7 miles across and 7640 feet high. This island might be taken as the very type of a young, cliff-walled island, except that it has been recently and slightly tilted on a northeast-southwest axis a little northwest of the island center, so that a crescentic area of its former abraded platform now stands a little above sea level around the northwest coast, where since emergence it has been somewhat cut back in low cliffs. This rock platform, in so far as it is laid bare, is one of the few that is observable instead of being only inferable.

The *Challenger* Narrative (1885, p. 241) describes the island as follows: "Precipitous cliffs, 1000 to 2000 feet in height, rise directly from the sea everywhere, except in the northwest quadrant, where there is, in front of the cliffs, an irregular flat, 100 to 200 feet above sea level. . . . Its coast may be fitly described as iron-bound. . . . Streams, or rather cascades, which come dashing down to the sea [from the little-dissected slopes of the cone above the cliffs] during the constant heavy rains, have eaten their way into the cliffs and their beds form conspicuous features in the view as

narrow gullies, descending the rocks in a series of narrow steps." Hence, in so far as valleys have been cut in the upper slopes of the cone, their mouths hang high above sea level in the face of the great cliffs. There could be no more conclusive proof that open ocean abrasion proceeds much more rapidly than short-stream erosion, even on an island that has a steep slope and receives a heavy rainfall. The view of the island (Fig. 64), reproduced from the *Challenger* report, perhaps gives the gentle slopes above the cliffs too much the appearance of a level plain.

The events of a three-year residence on this remote island are told by Mrs. Barrow, wife of a missionary (1910), with occasional descriptions and photographs of the island forms, from which it appears that the cliffs are frequently beached at their base and are occasionally fronted by isolated rocks in the form of stacks or skerries. It is also recorded that the ravines in the cliffs which face northwest over the "irregular flat" or emerged rock platform—known to the few inhabitants as the "settlement plateau"—lead down to large detrital fans, one of which is well shown in a plate in the voyage of the *Quest* (1923). All these fans have evidently been formed since the "plateau" was uplifted; for no fans accumulate elsewhere on the surf-beaten beach. This interpretation is confirmed by a large-scale inset on HO 3902, part of which is here included at the bottom of Figure 63. Here the "plateau" below the great cliffs of the central cone is seen to have a ragged cliff up to 100 feet in height along its outer edge, evidently the cut-back margin of the uptilted rock platform. The near-by soundings do not suffice to define the area or depth of so much of the normal platform as remains submerged. From a legend on the chart it appears that a field of kelp, rooted in 15 fathoms and stretching a third of a mile offshore from the ragged young cliff of the up-tilted platform, subdues the surf there and allows boats to land or to water with a hose from a shore waterfall.

Other islands in the Tristan da Cunha region are: Inaccessible, HO 3902, a tabular mass 2 or 3 miles across, about 1100 feet high, and with the highest summit at 1840 feet. Cliffs up to 1000 feet in height rise on nearly all sides, exposing according to the *Challenger* observers (1885, p. 257) successive layers of basalt traversed by dikes; streams cascade down the cliffs, and discontinuous beaches lie at their base. A circuit of soundings 1 or 2 miles offshore give depths of 75, 65, 52, 65, 84, 90, 90, 56, 90, and 75 fathoms, thus indicating the occurrence of a rather low-lying bank, one of the best of its kind. Nightingale, HO 3902, a mile across, of uneven upland surface, 1105 feet high, is cliffed all around; two smaller rocks, both cliffed, stand near by on the north. Cliff-base caves are reported on this island by the *Challenger*, thus suggesting an early stage of abrasion; two views of the island are given in the same volume (1885, pp. 264, 265). According to Buchanan, a member of the *Challenger* staff, the island bears marks of an elevated shore line at a height of 35 feet (1876, p. 615). A circuit of soundings 1 or 2 miles from the island gives

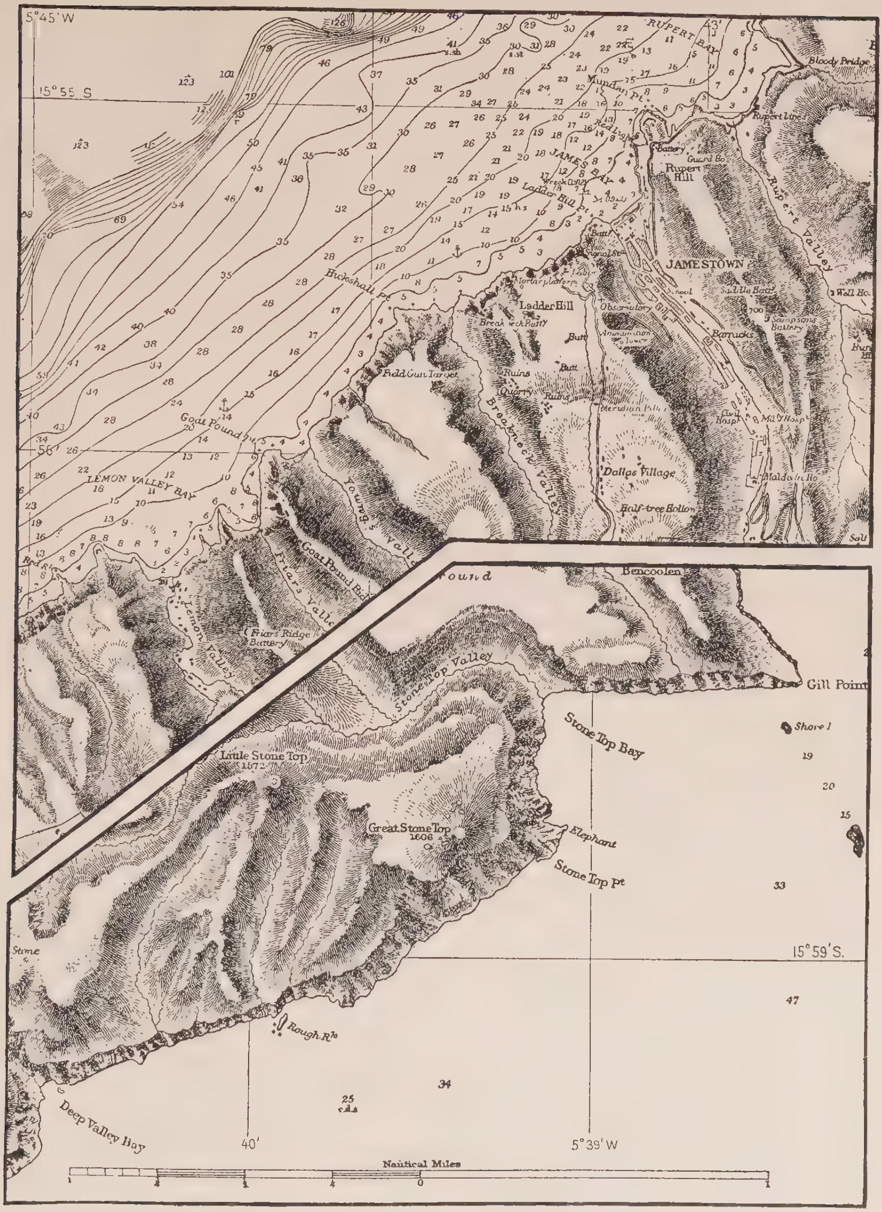


FIG. 65—Northwest and southeast coasts of St. Helena, South Atlantic; HO 3901. Submarine contours are added off the northwest coast.

depths of 190, 150, 150, 110, 52, 70, 210, 190, and 200 fathoms. Gough, HO 3902, 8 by 4 miles, 4380 feet high, has cliffs from 200 to 1000 feet high nearly all around the shore; few near-by soundings are charted. Views of Inaccessible and Gough islands are given in the voyage of the *Quest* (1923). The soundings around Inaccessible and Nightingale suggest subsidence.

St. Helena

Just as Tristan da Cunha may serve as the type of a young, cliff-walled volcanic island, St. Helena, HO 3901 (Fig. 65), 5 by 8 miles across, 2700 feet high, may be taken as the type of a maturely dissected, cliff-walled volcanic island. The difference between the two is found chiefly in the slight dissection of the first and the deep dissection of the second. In Tristan da Cunha the upper parts of the cone are little changed from the initial form of eruption; in St. Helena the initial cone is reduced to serrate ridges between deep-cut valleys; the coast is cut back in bold sea cliffs rising from 200 to 1500 feet or more. The topography of the island is well shown on a map, No. 1853, issued by the Intelligence Division of the British War Office, on a scale of 2½ inches to a mile, the relief being indicated by brown shading with 100-foot contours.

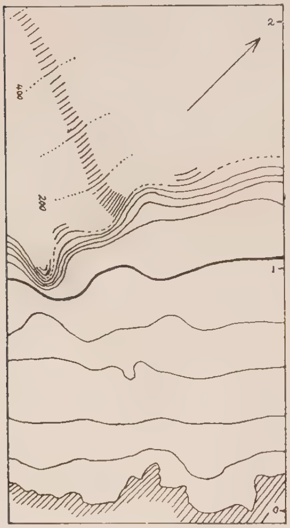


FIG. 66—Submarine contours for the north coast of St. Helena, based on HO 3907.

Darwin noted that "the entire circuit of the island has been deeply worn back into the grandest precipices" (1844, p. 93). All the smaller valleys appear to have hanging mouths, some of which are well shown in Figure 65. The largest valleys have flat floors for a little distance inland from their mouths, as if they had been eroded somewhat below normal ocean level during the last Glacial epoch and somewhat aggraded in consequence of slight submergence when the ocean rose again in Postglacial time. The island is surrounded by a bank with depths of 8 or 10 fathoms near shore and marginal depths of 50 or 60 fathoms, beyond which a rapid descent is made to several hundred fathoms, as is shown by submarine contours that I have added in Figures 65 and 66.

Daly, who visited St. Helena in 1921, gives an excellent geological account of it (1922). He detected in the cliffs "on its leeward side . . . numerous sea-caves and rock-benches" about 20 feet above present sea level. "On the windward side . . . the 20-foot strand marks have apparently been already destroyed. The more moderate, although absolutely powerful surf on the leeward side has damaged the 20-foot benches, but has left many remnants." He ascribed the emergence of these benches to a eustatic lowering of sea level of the same date as that which he had earlier inferred for Tutuila in Samoa and certain other islands (1920); and he concludes that St. Helena "has neither sunk nor risen for a very long period of time, if, indeed; it has moved at all since the distant epoch of its last eruption." Since its eruptive growth it has

"suffered denudation and sea-cliffing to such degrees that a late Tertiary origin seems preferable to one even in the early Pleistocene" (1922, p. 155, 156).

This attribution of a somewhat remote date for the origin of a volcanic island that is dissected only by narrow valleys gives support to a view presented on various pages of this volume; namely, that the well-opened valleys occupied by embayments in many reef-encircled volcanic islands of the Pacific coral seas cannot have been excavated only during the Glacial epochs of lowered ocean level; they must have been chiefly excavated by longer-enduring Preglacial erosion with respect to normal ocean level and only subordinately modified, after their submergence had been begun as a result of subsidence, by low-level erosion in the Glacial epochs. Hence it may be inferred that the transformation of an unprotected, walled island like St. Helena into the substellate form of Banks Peninsula can be accomplished only by a relatively rapid subsidence. This point will be later adverted to under the phrase, "Banks-Helena contrast." The bank around this island retains no trace of a bench of low-level abrasion, such as it might be expected to bear if the island, always standing still, had been actively attacked by the waves of the lowered ocean during the several Glacial epochs of the Glacial period.

Mid-Atlantic Islands

Ascension, about 400 miles northwest of St. Helena, HO 538, 7 by 6 miles, 2817 feet high, is a much younger island than Tristan da Cunha; part of its borders show initial lava-flow salients alternating with coves; other parts of earlier formation are moderately cliffed, depths of 110 or 120 fathoms are found a mile or two from shore. This island has been well described by Daly (1922). Trinidad, 20½° S, 29½° W, off the coast of Brazil—not to be confused with the larger Trinidad near Venezuela—is about two miles across and 2020 feet high. Its cliffed and embayed shores are said to be surrounded by sharp, rugged "coral" rocks; hence this island may belong in the Atlantic marginal belt. Some of the good-sized volcanic islands in the Gulf of Guinea, HO 2202, are peculiar in having moderately embayed shore lines. The banks around them have about normal marginal depths. There appears to be little question that these islands have subsided in moderate measure, but the aggradation of the encircling banks seems to have kept pace with the subsidence.

Volcanic Islands of the Atlantis Region

The Atlantis region of the eastern North Atlantic contains a good number of relatively young volcanic islands. While no final judgment can be safely pronounced as to whether they are stable, rising, or subsiding without study of the islands themselves, the variations of bank depths are so considerable as to suggest instability rather than stability. Fur-

thermore, in view of the upheaval of some of the islands by smaller or larger amounts, as indicated by marine deposits on their slopes, instability is more expectable than stability. But whatever subsidence has taken place has not been sufficient in amount or in rapidity to produce well defined drowned-valley embayments. The islands have relatively simple shore lines, and such irregularities as occur appear to be the result of abrasion.

The banks around the Cape Verde Islands are imperfectly sounded; but two island-free banks in the eastern part of this group, as well as the rock-crowned banks known as the Salvages farther north, are significant as apparently representing recently consumed islands. The banks adjoining Lanzarote and Gomera in the Canaries and those adjoining Flores and Graciosa in the Azores, as well as those of the cliffed residuals known as Deserta in the Madeira group, have a marginal depth of about 70 fathoms, which might be interpreted as meaning that the effects of low-level abrasion have not been fully concealed by aggradation since the return of the ocean to its normal level; but, as the great majority of the banks around other islands have normal marginal depths of 40 or 50 fathoms, it seems not improbable that the deep-margined banks indicate recent subsidence.

Submarine Banks of the North Atlantic

Many banks of various depths are known in the North Atlantic, probably because this ocean has been more generally sounded than any other; but few if any of the banks possess the well defined tabular form of small depth that should result from either normal or low-level abrasion of a stationary island. The chief examples are as follows:

Five banks are charted, HO 1743, between the Cape Verde Islands and the African coast; their approximate dimensions, taken from the 100-fathom line on the chart when more than one sounding is recorded, are as follows: Santa Rita, 16½° N, 21° W, 77 fathoms; Birkenhead, 17° N, 20° W, 86 fathoms; a bank "reported 1910," 18° N, 18° W, 27 fathoms; Doric, 19° N, 18° W, 56 fathoms; Maceio, 19½° N, 20½° W, 65 fathoms. Six banks are shown on the same chart between the Canary and Madeira Islands on the southwest and Morocco and Portugal on the northeast: Conception, 30° N, 12½° W, 88, 98 fathoms, 3 miles across; Dacia, 31° N, 14° W, 12 to 60 fathoms, 10 miles across, described by Buchanan (1886); a bank near by on the east, 70 fathoms; Seine, 33½° N, 13° W, 81 fathoms; Josephine, 36½° N, 14° W, 82 fathoms; Gettysburg, or Gorringe, 36½° N, 11½° W, 30 fathoms, 4 by 2 miles. None of these banks are known well enough to determine whether they represent the remains of former volcanic islands more or less abraded and subsided or the unmodified tops of volcanic cones that never reached the ocean surface.

Other banks shown on North Atlantic charts, HO 955, 956, are: Prin-

cesse Alice, southwest of the Azores, 38° N, 29½° W, HO 5384, 24, 43, 47 fathoms; its 100-fathom contour is 2 miles across and its 200-fathom contour 7 miles across; Marsala, 34° N, 34° W, 82 fathoms; Sainthill, 42½° N, 42° W, 100 fathoms; Milne, "existence doubtful," 42½° N, 39° W, 81, 100 fathoms; Chaucer, "existence doubtful," 42½° N, 29° W, 48, 50, 70 fathoms, 30 by 15 miles; Laura-Ethel, 47° N, 39° W, 36 fathoms; the great Newfoundland bank, HO 1412, 200 by 250 miles, with many soundings about 40 fathoms; to the east, Flemish Cap, HO 1138, 47° N, 44° W, 72 to 90 fathoms, 50 by 25 miles, generally with a gradual slope to depths of about 200 fathoms over a large area; Porcupine, 53° N, 16° W, 84, 86, 95 fathoms, 45 by 15 miles.

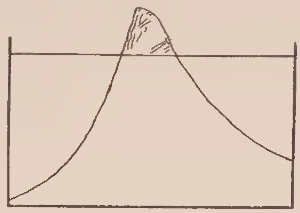


FIG. 67—Profile of Rockall, North Atlantic.

Far to the southwest, HO chart 955a shows three banks: One, "reported 1881," 300 miles off the northeast coast of Brazil, 5° N, 46° W, 52 fathoms; Madiana, 14½° N, 61° W, 44 to 88 fathoms, 12 miles long; Echo, 300 miles northeast of the Lesser Antilles, 21° N, 59° W, "existence doubtful," 34 fathoms.

The Islet of Rockall

The islet of Rockall, west of Scotland, 58° N, 13½° W, HO 4430, surmounts an extensive bank, with depths from 50 to 100 fathoms over an area of 70 by 30 miles, while depths down to 200 fathoms extend over an area of 150 by 50 miles. The islet (Fig. 67)—see Green (1897) and Charcot (1922)—is only 250 feet in circumference and about 70 feet high; it is "a portion of a great intrusive sheet of igneous rock, now lying in an inclined position upon stratified masses, which are seen on the southwest side of the rock" (1897, p. 49). Depths of 20 and 30 fathoms are found close by. Its submarine profile is better determined than that of any other open-ocean rock. A trawl brought up from 80 fathoms not far away "a most unexpected assortment of shallow water shells, evidently long since dead," also volcanic pebbles and gravel; the islet "must be the relic of a mountainous island" (1897, pp. 45, 97). This great bank may have been modified near the islet by low-level abrasion in the Glacial period, but it is as a whole far too deep and too extensive to have been formed in that way then. It can hardly be explained without subsidence.

Three smaller banks occur between the Rockall bank and the Faroe Islands: Outer Baily, 38 by 20 miles, from 100 to 200 fathoms deep; Bill Baily, 20 miles across, from 63 to 85 fathoms deep; and Faroe bank, 40 by 25 miles, 49 to 80 fathoms deep; they all suggest subsidence.

The Faroe Islands

The Faroe Islands, BA 117, 60 by 30 miles over all, may be briefly mentioned as having suffered strong glacial erosion; their peculiar forms are

beautifully shown in a series of topographical maps published by the Danish government. They are surrounded by a bank measuring 130 by 110 miles, with a marginal depth of about 70 fathoms.

Regarding the above-noted North Atlantic banks, it may be said that the two larger ones, namely, Newfoundland and Rockall, seem to be related rather to continental than to oceanic structures and processes; they probably have little bearing upon our problem. The Faroe bank has been affected by Glacial action. The smaller banks are of indeterminate origin.

Summary for the Cooler Seas

The cooler seas of the North and South Pacific and of the South Indian Ocean give no mid-ocean examples of banks that can be safely regarded as representing stable islands nearly or completely truncated by normal or by low-level abrasion, although some such banks may yet be found in the far southern part of the Indian Ocean, when more soundings are taken in the neighborhood of the strongly cliffed islands there occurring. The few banks that occur south of Japan are in close association with islands of recent eruption; hence, even if subsidence is there prevalent, it would appear that the banks are still too young to be deeply submerged. In the cooler seas of the Atlantic many more submarine banks are known. The dimensions of some of them are such as to imply a large amount of abrasion in their production, but their depths vary so greatly as to suggest that the vanished islands have been unstable and often subsiding rather than stationary. Here also, however, some of the banks are associated with relatively young islands, and for such banks deep submergence is not to be expected even if slow subsidence is in progress. The rarity or absence of uplifted and benched islands in all the cooler seas shows that upheaval has been unusual. The absence of well-embayed pelagic islands like Banks Peninsula shows that whatever subsidence pelagic islands have suffered has not been rapid or great enough to submerge the island valleys, the mouths of which are cut back by open-ocean abrasion.

It should, of course, be clearly understood that the absence of banks in the Pacific and Indian cooler seas might be accounted for by assuming that no volcanic islands have ever been formed there, instead of by supposing that after having been formed and more or less consumed they have disappeared by subsidence. But, when the relative abundance of banks of moderate depth in the narrow marginal belts of the coral seas is discovered and still more when the considerable number of banks in the coral seas is recognized, the assumption that no volcanic islands have ever been formed in the blank areas of the cooler seas of the Pacific and Indian oceans seems unreasonable. For it is altogether improbable that the climatic boundary between the great oceanic areas of the cooler seas where banks are absent and the great oceanic areas of the warmer seas where they are present should also be the boundary between areas in which vol-

canic islands have not been formed and areas in which they have been formed. It is therefore concluded that this review of the cooler seas makes the subsidence of pelagic volcanic islands at a slow rate more probable than their stability.

It may be briefly remarked that the prevailing incompetence of nullipores alone to form reefs at all comparable to the reefs of the coral seas is clearly indicated by the absence of fringing, barrier, and atoll reefs from the cooler seas, in spite of the ability of nullipores to live in cool waters. Hence, whatever may be the importance of nullipores as reef binders, it would seem that corals must be the chief reef builders, for reefs are found only in the warmer seas where corals as well as nullipores can grow.

CHAPTER VIII

THE MARGINAL BELTS OF THE CORAL SEAS

Object of Inquiry

The object of the present chapter is to discover whether plunging-cliff islands surrounded by shallow banks, as deduced in Chapter VI, are to be found in belts lying between the cooler seas in which no coral reefs occur and the warmer seas in which coral reefs abound; and if so, to determine whether the islands show signs of subsidence, and to measure the width of the belts containing such islands.

No problem that I have ever attacked has illustrated better than this the importance of defining the postulates and deducing the consequences of various rival theories as impartially as possible in association with observational studies. Playfair gave excellent advice in this matter over a century ago. He wrote: "It would . . . be to argue strangely to say that we must wait till . . . discoveries are made before we begin any theoretical reasoning. . . . Such conduct would not be caution, but timidity, and an excess of prudence fatal to all philosophical inquiry. . . . The truth is, indeed, that in physical inquiries, the work of theory and observation must go hand in hand, and ought to be carried on at the same time, more especially if the matter is very complicated, for there the clue of theory is necessary to direct the observer" (Illustrations of the Huttonian Theory, 1802, p. 524).

It is of course possible that the discovery of the marginal belts of the coral seas might have eventually been made by blind induction—"blind" in being guided only by the outer sight without insight—but there can be no question that their discovery has been facilitated and hastened by the preliminary and intentional definition of the features that islands, either stationary or subsiding, should have, in case the marginal belts exist. Yet valuable as this particular clue of theory has been in the recognition and definition of these belts and in thus rounding out the whole theory of coral reef origins, it was not found until about seven years after my return from the Pacific voyage of 1914. It is as if, after exposure to the contagious facts of a problem has imparted to an observer the germs of a theorizing fever, a certain period of mental incubation has to be lived through before all the consequences of the exposure break out. After they do break out, the inner nature of the problem is made so clear that all previous inquiry seems like vague groping.

It should be here noted that, whatever the importance of nullipores may be as reef binders and however well they may survive the low temperature of deep waters in which they are said to grow even at depths of 1000

fathoms or more, they do not seem to have been competent to act as reef makers in the marginal belts of the coral seas when the surface waters there were somewhat chilled and the reef-building corals were killed during the Glacial epochs; for the facts to be presented in this chapter seem to make it clear that the reefs of the marginal belts were cut away by low-level abrasion during those epochs. Yet it cannot be supposed that the waters of the marginal belts were reduced to temperatures as low as those which prevail at depths of 1000 fathoms in the coral seas. Thus it would appear that corals are the controlling organisms of coral reefs, even though the associated nullipores are important as coral binders.

The North Pacific Marginal Belt

The marginal belt of the North Pacific is better defined through much of its course than that of any other ocean, because it possesses a considerable number of cliffed islands surrounded by submarine banks and a fair number of submarine banks without surmounting islands. But the eastern part of the belt is peculiar in being reduced to a very small breadth, if the little almost-atoll of Clipperton Rock be accepted as marking the limit of the coral seas north of the equator; for this almost-atoll stands only about 600 miles from the coast of Mexico and thus compresses both the marginal belt and a strip of the cooler seas into that small measure.

The Islands and Banks of the Hawaiian Chain

The long chain of the Hawaiian islands, HO 1216, begins with 8 large or medium-sized members, CS 4102, which occupy a stretch of 375 miles on the southeast between latitude 19½° and 21½° N, and is continued by an extraordinary series of islets, rimless banks, and bank atolls, HO 2, 4, for 1000 miles farther northwestward to latitude 28½° N. A good list of references to many scientific accounts of the larger islands has been prepared by Marcuse (1894), and a general account of Hawaiian reefs has lately been published by MacCaughey (1918). The following account of the larger islands, with special reference to their coastal features, begins with the youngest, largest, and southeasternmost of the series.

The Island of Hawaii

Hawaii, CS 4115, 80 by 65 miles, consists chiefly of two large and confluent cones of very gentle slope, Mauna Loa, 13,675 feet high, the more active of the two, on the south, and Mauna Kea, 13,825 feet high, on the north. These young and lofty cones are of later origin than the smaller and much older, deeply dissected mass of Kohala, 5505 feet high, north of Mauna Kea; while the lower and frequently active caldron of Kilauea, 4088 feet high, lies south of Mauna Loa. The slopes of the lofty younger

cones not infrequently exhibit fractures, on which slight depressions of exterior segments have occurred. The coastal margin of the cones, which forms the greater part of the island's perimeter, is moderately cliffed, with many streams cascading into the sea from hanging valleys. Its minutely ragged pattern is characteristic of young cliffs of small retreat or of refreshed cliffs that are kept young by slow submergence in spite of greater retreat. The shore is prevailingly free from fringing reefs, as is expectable on young volcanic islands; but, as beaches appear to be absent or poorly developed, the absence of reefs may be chiefly due to the low temperature of the ocean water. The coast of the island has not, however, received the attention it deserves from recent visitors to Hawaii, who have given their time almost wholly to its remarkable volcanic features.

Evidence of subsidence in Hawaii was nevertheless detected by Branner a quarter century ago, in connection with the history of its older northern volcano, Kohala. Some lava flows from Mauna Kea encroached upon and nearly buried the Kohala mass, as Dana long ago pointed out (1849, p. 284); but its northeastern slope, known as the Waipio district, was not reached, and still exhibits great canyons of submature erosion, such as are presumably buried on the opposite slope. High cliffs are cut back where the inter-canyon spurs reach the sea. These features are beautifully shown on the contoured maps, 1:62,500, of the Waipio quadrangle issued by the United States Geological Survey. On the other hand, the fine-textured radial dissection and the ragged cliffing of the younger Mauna Kea slopes, which reach the shore by lapping around the dissected Kohala mass on its northwest and southeast sides, are finely represented on the maps of the Kohala, Waipio, Hamakua, and Honomu quadrangles.

Branner wrote as follows regarding this instructive district: "The bluffs facing the area [misprint for sea?] have an elevation of a thousand feet, and enormous gorges extend inland with almost precipitous walls, some of which it is said are as much as 2000 feet in height. . . . The largest of them [the gorges] have flat bottoms. . . . The great height of the sea bluffs is due to the long encroachment of the sea upon this old land margin. The flat bottom of the largest of these canyons is due to the fact that the canyons were formed as V-shaped gorges on the land and have sunk until their lower ends were filled by the sea, forming deep fjords which were soon filled by the material cut by the waves from the headlands and thrown back into them, and by the débris brought down from the land by the streams" (1903, pp. 301–303). A landslide at the base of one of the cliffs is noted on CS chart 4115; Ellis gave the date of the slide as 1820 (1825, p. 209).

Whether the great cliffs of the Waipio district were cut back by the sea as Branner believed and as seems probable in view of the correlated erosion of valleys behind the cliffs, or whether they result from downfaulting as Powers has suggested (1917, p. 511) is at present immaterial. In

either case the form of the canyons and of their alluvial floors makes it probable that submergence has taken place since the canyons were cut. A careful construction of longitudinal and cross profiles of the chief canyon, Figure 68—the construction being guided by three cross profiles, *P*, *Q*, *R*, farther inland—indicates that its rock-bottom mouth in the plunging cliff face, *CF*, may lie at a depth of several hundred feet, and even there it may not have been cut down to the sea level of its time. So great a submergence must be ascribed chiefly to subsidence. As will appear below in

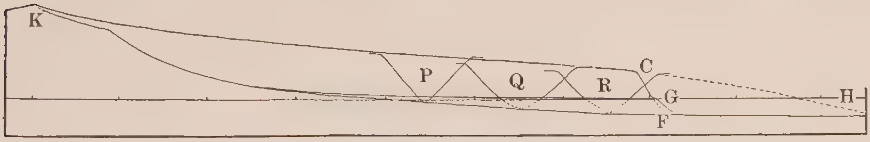


FIG. 68—Profile of partly submerged valley and sea cliff in the Hamakua district, northeast coast of the Island of Hawaii.

the case of an older western cone on Oahu, so here the subsidence of the older Kohala cone on Hawaii seems to have taken place during the building up of the younger and greater volcanoes near it. The absence of a barrier reef or of a submarine bank along the cliffed shore of the Kohala cone, in spite of the opportunity for reef upgrowth that the inferred subsidence might have provided, may be explained either as a result of too rapid subsidence or of too low ocean temperature.

Islands between Hawaii and Oahu

Maui, CS 4116, is a typical volcanic doublet. The larger eastern cone, 32 by 22 miles, 10,032 feet high, is of recent eruption and, although much broken down in its great breached caldera of Haleakala, is little dissected. The smaller western cone, 16 by 11 miles, 5788 feet high, is well dissected and has a strongly cliffed shore on the west and north. A short patch of fringing reef occurs in the northern reëntrant between the two cones. The bank around the island has a width of from 2 to 5 miles and falls off at 70 or 80 fathoms. Kahoolawe, CS 4116, 5 by 10 miles, 1450 feet high, moderately cliffed on the south, and Lanai, CS 4116, 10 by 15 miles, 3400 feet high, also moderately cliffed, do not seem to be important witnesses in our inquiry.

Molokai, CS 4116, 34 by 7 miles, 4970 feet high, is a doublet that has probably been much diminished from its original size by the downfaulting of its northern part; for the great cliff along the northern coast, which reaches heights of 2500 or 3500 feet in the eastern half of the island, appears to be a slightly modified fault scarp, which Dana long ago described (1849, p. 233; 1889, p. 95; 1890, p. 290) and of which Lindgren has given a later account (1903). The scarp is interrupted by great valleys, like those of the Kohala district in Hawaii, but without indication of so great a submergence. The south slope of the island is little dissected; its

coast is low and is bordered by one of the best fringing reefs in the group; it is nearly a mile in breadth for much of its many miles of length. Outwashed detrital deposits are advancing upon it opposite every large gulch: they may in time smother the growing corals on the reef face and thus permit the waves to cut the reef away, unless its life is prolonged by favorable submergence. Small patches of elevated reef are found 25 feet above sea level; at one point a reef patch stands 130 feet above the sea: hence the

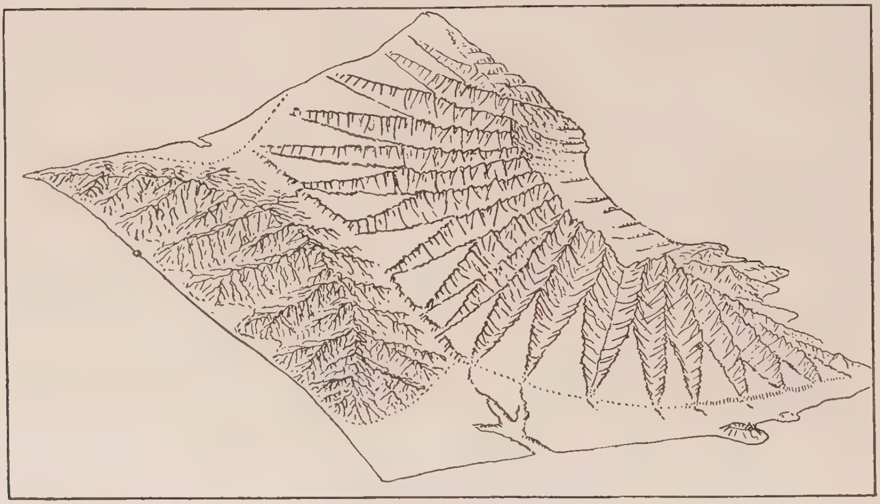


FIG. 69—Bird's-eye diagram of Oahu, Hawaii.

present sea-level fringe lies on a shore of emergence. A rather rapid descent to deep water is made outside of the reef, except on the southwest where a shoal extends for 25 miles. At the end of this shoal a very smooth and somewhat shallower area, measuring 12 by 8 miles, is known as the Penguin bank and is from 25 to 30 fathoms in depth: it falls off rapidly to 200 or 300 fathoms. This smooth bank is the only example of its kind among the larger Hawaiian islands: its origin is unknown.

The Island of Oahu

Oahu, CS 4110, 20 by 32 miles (Fig. 69) is beautifully represented on a large one-sheet contoured map published by the U. S. Geological Survey on a scale of 1:62,500. This island was originally a domelike volcanic doublet similar to Maui; but it is now incomplete, inasmuch as the larger exterior segment of each dome has disappeared on the east and west, as if by downfaulting beneath the ocean. The remainder of the mass has the outline of an irregular trapezoid, measuring nearly 40 miles along its irregular northeastern side and 20 along its simpler western side, these two sides being from 20 to 30 miles apart. The southern side, pieced out by a low

plain of coral limestone, trends east-west: Honolulu is situated near its mid-length. The opposite or northern side of the island trends nearly northeast-southwest. The sharply serrate crest of the eastern, windward, and younger dome remnant is known as the Koolau Range; it is densely forested up to its summits, which rise 2500 or 3000 feet and culminate in Konahuanui peak, 3105 feet. The range descends rapidly toward the northeastern shore in a dissected and precipitous scarp, which in its high-

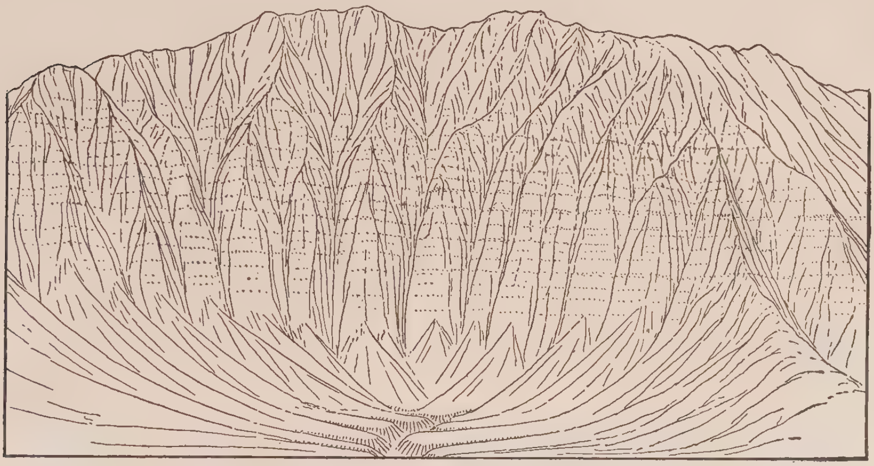


FIG. 70—Diagrammatic sketch of part of the Pali cliffs, northeastern side of Oahu.

est, steepest, and most retreated medial part forms a great cliff, receding in several shallow bights between blunt cusps (Fig. 70) and famous in Hawaiian history under the name of the Pali; a more gradual descent, following the slope of the lava beds in its lower part, is made toward the west. The western, leeward, and older dome remnant rises in the Waianae Range, culminating in Mt. Kaala, 4030 feet. This range, which is more maturely dissected and much less verdant than the other, stands five or six miles back from the western shore, to which a more gradual descent than the Pali is made by broadly opened valleys between narrowed spurs. The greater dissection of the western segment clearly indicates that it is of earlier origin than the eastern; and this indication is confirmed by the manner in which the submaturely dissected inland slope of the eastern segment overlaps the late-maturely dissected inland slope of the western in a broad saddle at an altitude of 850 feet; there, near the island center, is the salubrious site of Schofield Barracks. Recently renewed but very subordinate volcanic activity has produced several small craters on the southern and eastern sides of the Koolau segment.

Reduction of Oahu by Downfaulting

The disappearance of the larger exterior segments of the two domes, the initial forms of which are indicated in the dotted lines of Figure 71, has

been the subject of much speculation. Dana, who long ago recognized the composite structure of the island and who also saw that the eastern dome was younger than the western, suggested that the lost segments had "disappeared beneath the sea" (1849, pp. 257, 259; 1890, p. 301) as if by engulfment; but it has also been thought that the missing parts have been removed by subaerial and marine erosion. Dutton was one of the observers who adopted this view; he concluded that the northeastern or wind-

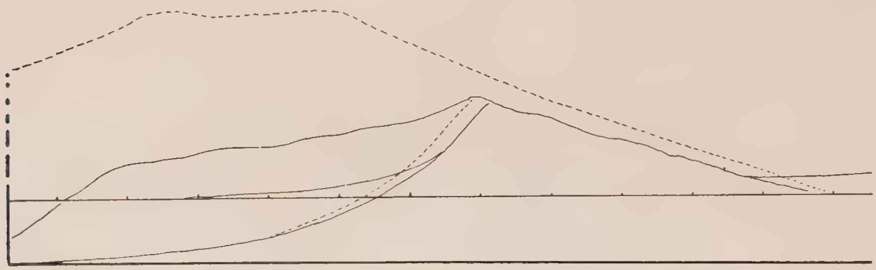
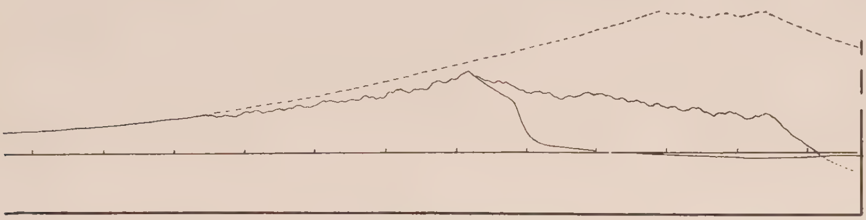


Fig. 71—Profile across Oahu, with dotted lines

ward side of the Koolau dome has been "almost completely swept away by erosion" and that the difference in the amount of erosion on the two sides of the mass was "unquestionably due to the difference of precipitation" (1884, pp. 213, 214); Hitchcock later expressed a similar opinion (1909, p. 21). But neither of these authors recognized that if the northeastern dome has been consumed chiefly by erosion, a lowland or a shallow submarine platform ought to remain in its place, unless a great subsidence of the worndown mass had taken place since its downwearing. If subsidence is thus admitted, it may have occurred in larger amount before the inferred erosion had been accomplished, as well as in smaller amount afterward. The sea is now 100 or 200 fathoms in depth offshore from the northeastern coast, where the lost summit of the dome, as indicated by the upslopes of the lava beds in the surviving segment, is supposed to have risen. In any case the excess of precipitation on the windward over the leeward slopes of the island cannot have determined the removal of a lost part of a volcanic dome; for, while the vanished segment of the younger dome is truly on the windward or rainy coast, the vanished segment of the older dome is on the leeward or dry side.

The origin of the Pali has been variously explained. As already noted, it stands well back from the shore where it is highest and steepest through the mid-length of the northeastern coast. The short, heavy and steep-ending spurs to the north and the longer spurs to the southeast of the Pali (Fig. 69) extend farther toward the sea. All this bold northeastern slope must have been primarily part of the scarp left when the lost segment of the dome sank into the ocean. Since then the mid-length of the scarp has retreated into the several concave bights of the Pali, leaving the longer

spurs on the northeast and southeast more outstanding. The reason for the accelerated retreat of the Pali as well as for its greater height and steepness seems to lie in the arched structure of the volcanic mass as exposed along the face of the surviving volcanic segment; for, because of that arched structure, a basal series of weaker beds underlying a heavy series of more resistant beds is there exposed to erosion. I believe it is chiefly by reason of the sapping of the cliff face by the rapid retreat of these weak underlying beds that the extra recession and the unusual steep-



indicating inferred initial profiles of its two volcanoes.

ness of the Pali have been caused. In confirmation of this suggestion, mention may be made of the exposure of the same series of weaker and less resistant underlying beds and the recurrence of a Pali-like cliff at the head of a southward discharging valley, by which the culminating peak, Konahuanui, is sapped on its precipitous southwest side, as shown in Figure 72.

A fine road leads from Honolulu on the southern limestone plain up Nuuanu valley—one of the many radial consequent valleys in the surviving segment of the younger dome—to a deep notch, 1207 feet in altitude, in the Koolau range, not far north of Konahuanui peak and next south of the Pali. From the notch the road descends to an alluvial lowland that lies between the base of the retreated Pali and the east coast. The detritus of the lowland seems to bank up unconformably against the base of the Pali in a steep talus; and the talus as well as the lowland is somewhat dissected. Some of the advancing spurs southeast of the Pali bear little fringing reefs at a small altitude above sea level. This is interpreted as follows: First, before the talus banked up against the Pali, the island stood higher than at present, so that the sapping of the cliffs was effective below their now visible base. Second, the island sank a few hundred feet, permitting the forward accumulation of the alluvial lowland and the backward growth of the upbanking talus. Third, a small emergence followed, in consequence of which the lowland and the talus were somewhat dissected. A fourth episode of slight submergence is indicated by little embayments in the lowland valley mouths. Evidence of a similar series of changes is found elsewhere on Oahu, as appears from an examination of its emerged coral reefs and their associated limestones.

FIG. 72—Konahuanui, at the head of Manoa valley in the Koolau range of Oahu, looking northeast.

FIG. 73—A mountainous spur end, advancing seaward south of the Pali, northeast coast of Oahu; a slightly elevated coral reef lies at the base of the spur.

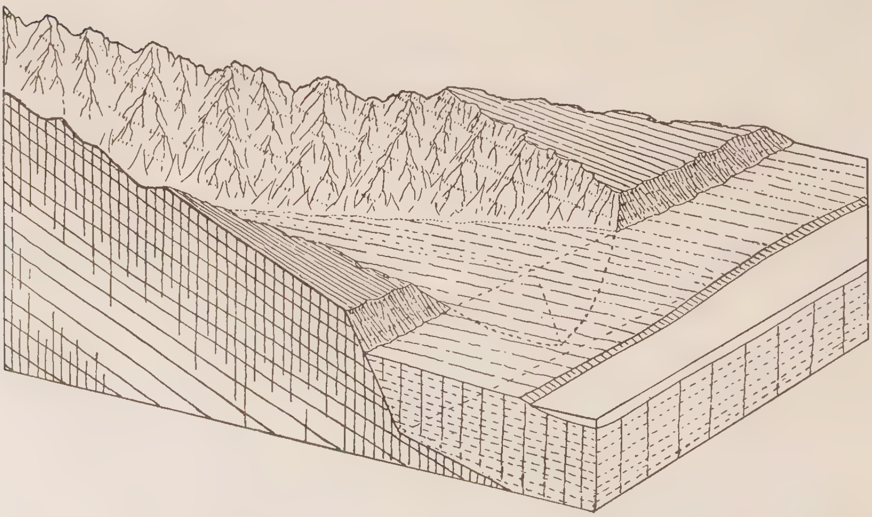


FIG. 74—Block diagram of Wailupe valley embayed by coral-bearing limestones, southeastern Oahu; the left-front section shows the depths to which the spur-end cliffs and the coral-bearing limestones are thought to descend below sea level.

The Coral Limestones along the South Coast of Oahu

The discontinuous fringing reefs along the present shores of Oahu do not call for special attention here; their zoölogical features are described by Agassiz (1889). The belt of emerged coralliferous limestone forming the low plain along the southern coast is traceable with varying width around a large part of the island border, as shown on maps by Dana (1849, Pl. opp. p.233), Agassiz (1889, Pls. 4, 5), and Hitchcock (1900, Pl. 1). The alti-

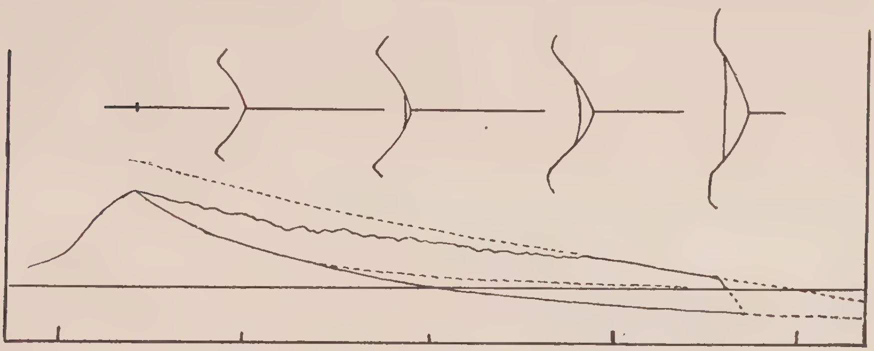


FIG. 75—Profile and cross sections of Wailupe valley, southeastern Oahu.

tude of the inner margin of the plain is about 25 feet; its greatest breadth is along the western part of the southern coast, where it reaches two or three miles. The limestones in this part of the plain are continuous with and sometimes interbedded with stratified tuffs, especially in the southern reëntrant between the surviving segments of the two volcanic domes, where the coastal plain locally gains an inland reach of five miles. The limestones of this plain appear to represent an emerged lagoon floor; but the outer margin of the plain is nowhere enclosed by a barrier-reef wall, such as surrounds much of the lagoon plain in the elevated atolls of Lifu and Mare in the Loyalty group northeast of New Caledonia, to be described in Chapter XV. Hence the former barrier reef of Oahu has probably been removed and part of the plain behind it consumed by abrasion in a late Glacial epoch.

The relation of the limestone plain to the valleys in the southern slope of the Koolau range is highly significant; it is well exhibited in Wailupe valley, several miles east of Honolulu. There the lagoon limestones, containing an abundance of fossil corals, enter the valley for 600 or 800 feet back from the line of volcanic spur ends, or "line of outposts," as it may be called. Clearly, therefore, the limestones and the barrier reef which presumably once enclosed them must have been formed in association with submergence, after the Koolau valleys had been eroded.

The spur ends between the Koolau valleys east of Honolulu are dis-

tinctly cut off in slanting cliffs (Fig. 74) where the bedded lavas of the eastern dome are seen to outcrop in downsloping or basset edges. Evidently the cliffs plunge below sea level: they must have been cut back by waves during the time of higher stand in which the valleys were eroded; and surely no protecting reefs could have been present while the cliffs were retreating under wave attack. It is therefore probable that the cliffing was done while the young valleys of the eastern cone were supplying abundant detritus to the shore and thus preventing reef growth; but growth may also have been then prevented by the lowered ocean temperature of an early Glacial epoch. A reconstruction of the longitudinal profile of Wailupe valley and of four cross profiles, Figure 75, was made from the contour map of the island, to determine the rock-bottom depth of the valley mouth in the submerged face of the plunging cliff. If the valley mouth hung above the shore line, as is usually the case during the erosion and abrasion of a young volcano, the measure of submergence that has taken place here would be more than 700 feet and therefore much too great to be accounted for by Glacial changes of sea level alone; subsidence also must have taken place. Perhaps the most significant of all the inferences here made is that the cessation of further abrasion and the formation of the lagoon limestones back of the assumed barrier reef appear to have been prompted by the subsidence which the depth of the limestone-filled valleys demands.

Artesian Wells on Oahu

Good evidence regarding the thickness of the limestones in the southern plain is given by the records of artesian wells. Logs from a number of wells that have been bored in and near Honolulu were submitted to me by Mr. C. B. Andrews of that city, along with his discussion of them in an unpublished thesis. Those near the Koolau spur ends penetrated much "clay," presumably meaning fine, outwashed volcanic detritus; those farther seaward penetrated beds of "coral" of increasing thickness. In Campbell's 1500-foot well, near the shore, "hard white coral, like marble," was penetrated between depths of 320 and 825 feet; "brown clay with broken coral" was found between 1068 and 1178 feet; this being the greatest depth at which any "coral" has been reported. Lava was reached in this well at 1251 feet and penetrated 249 feet farther. In Foster's well, farther inland, lava was reached at 740 feet. By comparing the records of many different wells, the lava beds are found to have a seaward dip of about 10°, while the "coral" beds seem to lie about horizontal, as Branner recognized (1903, p. 315). This accords better with their formation as lagoon deposits back of an upgrowing barrier reef on a subsiding foundation, as above inferred, than as the advancing talus deposits of an outgrowing reef on a stationary foundation. The depth at which lava was reached in Foster's well gives gratifying confirmation for the estimated rock-bottom depth of Wailupe valley, as stated above.

The Southern Limestone Plain

The southern limestone plain is occupied in its widest part, in front of the southern inter-cone reëntrant, by the branching embayments or "lochs" of Pearl Harbor, which, as Branner pointed out, have been "formed by the depression beneath the sea of a small group of dendritic valleys previously carved by subaerial erosion in horizontal beds" (1903, p. 303). The ends of the land arms that divide the lochs in the harbor are now somewhat cut back in low bluffs, giving good sections of the structure of the plain for a small depth; and the heads of the lochs are filled in with delta marshes, thus indicating that the latest submergence is of recent date. The fossils here found are, according to Bryan, characteristic of enclosed waters, not of exposed reefs; this again supports the view that the limestone plain represents a lagoon back of a barrier reef, now vanished.

Pearl Harbor is the best and largest example of a drowned valley in the Oahu limestone plain, presumably because the trunk stream that crossed it there was of large size by reason of its gathering drainage from the convergent slopes of a large part of both dome segments. The drainage area of this trunk stream includes about a fifth of the whole island, or roughly eight times more than the largest of all the other single-valley areas. It should be noted that the changes of levels here inferred for the south coast —namely, a former higher stand, a subsidence of several hundred feet, a moderate emergence, and a smaller submergence—are the same as those inferred for the northeast coast, although the features of the two coasts are of altogether unlike character. The episode of emergence during which the Pearl Harbor valleys were cut in the southern plain must evidently have been much shorter and much later than the period during which the limestone-filled valleys of the southern Koolau slope were eroded. The emergence episode may therefore have well been the last Glacial epoch of lowered sea level, a fitting time for the abrasion of the inferred barrier reef.

The Western Valleys of Oahu

The broad valleys of the west coast are much more mature than the narrow valleys, northwest and southeast of the Pali, on the east coast. They are eight in number: four of larger, four of smaller size. Three of the latter are to the north and one to the south of the four larger ones. They are all separated by steep-sided spurs (Fig. 76) in which the gently inclined or nearly level lava beds suggest that the initial form of the volcano was an arched dome rather than a steep cone. The spurs do not taper down to the shore but end rather abruptly, as if they had been originally defined by the scarp on which the lost Kaala segment was downfaulted. Dana's map shows limestones in several of the western valleys, but the limestones of these valleys are nowhere enclosed by a barrier-reef wall. In one, Waianae, of the two larger valleys visited by me, a pit

near the shore and about 20 feet above sea level exposed three feet of creamy marl without bedding, overlain by two feet of well bedded chalky limestone. These calcareous beds, which must continue for a distance inland under the flat valley floor, appear to represent the quiet-water deposits of a former lagoon and thus give new support to the view that a barrier reef once rose a little distance offshore and has since been destroyed.

The other large western valley that I entered, Lualualei, is six miles long and four wide; it has a flat floor, which rises in an alluvial surface of

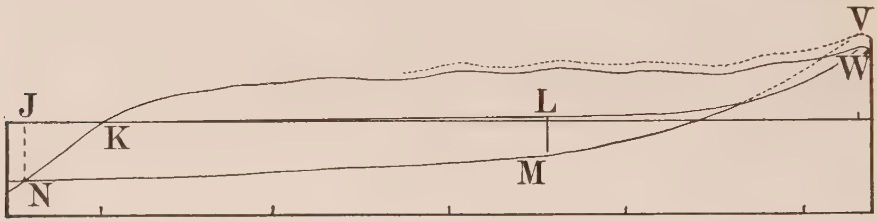


FIG. 76—Inferred underground profile of Lualualei valley, west coast of Oahu.

gradually increasing acclivity toward the valley head, where nearly horizontal lava beds outcrop, and with rapidly increasing acclivity at the valley sides. The limestones here seen near the shore resembled those of the south-coast plain; their inland extension is overwashed with detritus from the mountains. In all the large western valleys the steep sides of the inter-valley spurs taken with the breadth of the valley floors suggests that their rock-bottom depth must be at least 500 and more probably 1000 feet below present sea level. Thus one must here again infer a former higher stand of the island with associated valley erosion, followed, first, by strong subsidence and reef upgrowth and, later, by a small emergence and reef abrasion. The full measure of the strong subsidence is not well attested by the height of the valley limestones over the rock bottom of the valley; for these limestones appear to have been formed a little below sea level as lagoon floor deposits. The total subsidence is better measured by several small fringing reefs, standing at altitudes of from 60 to 120 feet and containing rather plentiful corals, on certain near-by spur ends, as described by Bryan (1916). They may be plausibly taken as onshore representatives of the vanished offshore barrier reef. No elevated reefs have been found at so great a height on the other sides of the island.

Well records from the western valleys collected by Bryan are of much significance. Wells near the valley sides pass through "soft earth and boulders" and then encounter solid lava at moderate depths, such as 75 feet. But those driven near the middle of the valley some distance back from the shore penetrate "river-bed sand and gravel" for great depths, as if located on heavy delta deposits. A well in Waianae valley passed through 20 feet of coral rock, from 30 to 50 feet below the surface, and

FIG. 77—The cliffed northwest coast of Kauai, Hawaii. (Photograph by N. E. A. Hinds.)

FIG. 78—The cliffed coast of Nühau, Hawaii. (Photograph by N. E. A. Hinds.)

then through 800 feet of "river-bed sand and gravel" without reaching solid lava. A well in Lualualei valley about two miles inland from the shore penetrated "soft earth" for the first 300 feet and "river-bed gravel and sand" for an additional 900 feet (1916, p. 117). A longitudinal profile of this valley on true scale, Figure 76, suggests that the original valley-head slope, *VM*, if continued with decreasing fall, would reach the shore of its time at *N*, while the present valley-head slope, *WL*, similarly continued, reaches the shore at *K*. This shows a rock-bottom depth, *LM*, for the former valley at the well, greater than the 1200-foot depth of the well, which did not reach solid rock, and hence a depth for the former valley mouth, *JN*, approximating 2000 feet. The greater depth of this submerged west-coast valley in the older volcanic mass than that of Wailupe valley on the south coast of the younger volcanic mass, suggests that the subsidence of the western mass began before the valleys of the eastern mass had been eroded, that is during the eruptional upbuilding of the eastern mass.

The North Coast of Oahu

On the north coast of Oahu, the reëntrant between the older and younger cones is occupied by the Waialua plain, composed in part of limestone about 15 feet above sea level and trenched by two little valleys entered by small bays, thus repeating the features of the southern plain but on a much smaller scale. The most novel feature of this coast is a well defined sea cliff, from 20 to 50 feet high, fronted by a nearly bare rock platform a quarter or half mile wide, where the northern slopes of the Koolau Range reach the shore northeast of the Waialua plain. The base of the cliff at the back of the platform is 20 or 25 feet above sea level. Part of the platform is now veneered with coral. It would thus appear that the sea was cutting away the volcanic slope on the northern salient of the island while a coral reef was forming across the Waialua reëntrant and all along the southern shore. Today the sea is again cutting away the sloping and reefless front of the rock platform and forming a low, ragged bluff some hundreds of yards in front of the abandoned cliff, while a fringing reef is growing on the southern shore.

The Oahu Bank

A bank of variable width surrounds Oahu. On the north it is 2 or 3 miles wide and falls off at 60 or 70 fathoms; on the east, 2 miles wide with a fall-off at 50 or 60 fathoms; on the south, 1 or 2 miles wide with fall-off at 40 or 50 fathoms; on the west, hardly a mile wide with fall-off at 40 or 50 fathoms. Soundings at greater depths are not numerous enough to define the form of the exterior slope. The margin of this bank may roughly represent the position of a former barrier reef cut down to a platform by low-level abrasion in the Glacial epochs. Thus explained, Oahu may be regarded as a marginal-belt island, yet standing so near the polar

side of its belt that Postglacial reefs are very incompletely developed around it.

The interpretation of the history of Oahu here offered takes fuller account of the observable facts than any other that has been proposed. Its most novel feature is the large measure of subsidence that it includes, for the subsidence of Oahu has generally been denied. Thus Agassiz, apparently not recognizing the significance of the limestones in the western and southern valleys or the occurrence of high-level unconformable fringing reefs and apparently adopting an obscure principle as to the origin of cinder cones, wrote: "There appears to be no evidence that there has been any considerable elevation in the Hawaiian islands, twenty to twenty-five feet being probably the extreme; while the existence of cinder cones with their base close to the present sea level would indicate also that there had been no special subsidence" (1889, p. 154). Again, in Hyatt and Pilsbry's study of the distribution of Hawaiian land shells it is inferred that great subsidence took place in Tertiary time, but the evidence given by the valley limestones for subsidence of much more recent date was not perceived. These authors concluded: "The absence of drowned valleys and fjords, as well as the great sea-cliffs where the waves have gnawed deep into the peripheral volcanic deposits, speak against recent subsidence. There is evidence of slight elevation in some places; but the islands seem to have remained practically stationary since the cessation of volcanic activity in the older masses" (1911, p. xii). Surely embayments smoothly occupied by coralliferous limestone are just as good evidence of recent submergence as embayments occupied by sea water.

Vulcanism and Subsidence

According to the interpretation for Oahu above proposed, its older Waianae and younger Koolau volcanoes repeat the testimony of the older Kohala and the younger Mauna Kea volcanoes of Hawaii as to the subsidence of the older mass while the younger one was building up on it. Similar testimony found elsewhere in the Pacific is of importance in correcting an inferred contrary relation that has gained currency in coral reef literature, to the effect that active volcanoes occur in regions of elevation and not in regions of subsidence. Darwin contributed to this view from a study of the chart he constructed showing the distribution of fringing reefs and active volcanoes, on the one hand, and of barrier reefs and atolls, on the other, regarding which he wrote: "It may, I think, be considered as almost established, that active volcanoes are often (not necessarily always) present in those areas where the subterranean motive power has lately forced, or is now forcing outward the crust of the earth, but that they are invariably absent in those, where the surface has lately subsided or is still subsiding" (1842, p. 140).

Forty years later, Murray went still farther and regarded the subsid-

ence of extinct as well as of active volcanoes improbable: "Generally speaking, all the volcanic regions which we know have in the main been areas of elevation, and we would expect the same to hold good in those vast and permanent hollows of the earth which are occupied by the waters of the ocean. . . . Areas of local depression are to be looked for in the ocean basins on either side of and between groups of volcanic islands and atolls, and not on the very site of these islands" (1880, p. 516). The same assumed association of eruption and upheaval seems to have guided Guppy to an unwarranted assertion: "In establishing the fact of the presence of active volcanoes in regions of barrier reefs and atolls, I shall be removing one of the principal standpoints of the theory of subsidence," and he therefore concluded that this inferred correlation places the "supporters of the subsidence theory in a dilemma" (1888, pp. 135, 136). Hickson was similarly led to an opinion adverse to the subsidence theory, for, when this zoölogist found an atoll near an active volcano north of Celebes, he wrote: "I am persuaded that the subsidence theory is not sufficient to account for all the facts, and that the presence of such an atoll as Passiac so close to a region of quite recent and considerable volcanic activity is difficult to account for under this theory" (1889, p. 42).

An opposite conclusion as to the relation of vulcanism and upheaval was reached for a continental island of the Atlantic by a highly competent geologist, Sir Archibald Geikie, who wrote: "A study of the records of volcanic action in Britain proves beyond dispute that the volcanoes of past time have been active on areas of the earth's surface that were sinking and not rising. . . . I do not wish to maintain that the downward movement was necessarily a consequence of volcanic ejections. . . . But I have sometimes asked myself whether it was not possibly increased as a sequel to vigorous volcanic action" (1897, Vol. 2, p. 470).

Molengraaff, one of the latest writers on this problem, has been led, as already noted, to the view that volcanic islands subside by their own weight (1916); that is, not simply that the upper part of the island settles down by a small amount as its great weight crushes the looser structures of the deeper part, as suggested by Daly (1915, p. 233), but that the weight of the entire mass causes a slow downbending of the suboceanic earth crust, as a result of which the island may eventually disappear. Its disappearance will of course be hastened by erosional loss of height while subsidence is in progress. Evidence will later be presented, based on the form of almost-atoll islets, to show that the two processes of erosion and subsidence contribute about equally to island disappearance. The independence of volcanic action and changes of level appears to be shown also by the work of the experienced Dutch geologists, Verbeek and Fennema, in their study of Java, where long continued volcanic activity has been associated with depression as well as with upheaval (1896, p. 1020).

Kauai and Niihau

Kauai, CS 4117, about 25 miles in diameter, 5170 feet high, is, like Oahu, finely represented on a single-sheet contoured map, 1:62,500, published by the U. S. Geological Survey. Facts and inferences regarding this island here presented are based largely upon information received from Dr. N. E. A. Hinds, who has lately studied it in detail. Its initial mass was a broadly arched dome; its eastern half appears to have been much lowered by engulfment, similar to that by which the Haleakala caldera has been formed on Maui. The western half of Kauai retains, on the contrary, much of its initial form, except that it is deeply eroded in consequent canyons and strongly cut back by high sea cliffs (Fig. 78). A number of the larger valleys are a little embayed. A crescentic strand plain, ten miles long and a mile wide, partly composed of fringing coral reefs, adjoins the cliff base on the west-southwest; and four borings here show a lava platform at a depth of about 300 feet. It would therefore appear that the great cliffs must plunge below present sea level and that since they were cut a submergence of 40 or 50 fathoms has taken place. The failure of reef growth during that submergence is significant. The height of the stronger cliffs, measured up from their submerged base, must be 2000 feet; and this, taken with the moderate lateral slopes of the initial dome, indicates a cliff recession of one or two miles at the very least. This measure of recession is confirmed by the bank that surrounds the island with about the same measure of width; it falls off to deeper water at 50 or 60 fathoms. A wall-and-bench notch, roughly of sine and cosine relation to the slant of the great cliffs, has been cut at present sea level; a cobble beach lies on the bench. Many of the smaller valleys have hanging mouths in the 2000-foot cliffs, from which their streams cascade to the beach.

Niihau, CS 4117, 16 by 4 miles, 1304 feet high, is a volcanic fragment, 15 miles west of Kauai; it is strongly cliffed on the southwest (Fig. 79) and is surrounded by a 2-or-3-mile bank, imperfectly charted.

Review of the Larger Hawaiian Islands

Although several of the larger Hawaiian volcanic islands are too young to show the effects of whatever subsidence they may be slowly undergoing, it is significant that two of their oldest volcanic masses, Kohala in Hawaii and the Kaala half-dome on Oahu, both give evidence of subsidence. It is furthermore interesting to note that, counter to a prevalent opinion which associates volcanic eruption with crustal upheaval, the subsidence of both these older masses appears to have been contemporaneous with the eruptive growth of younger volcanoes near by. The absence of embayments in the cliffed coast of the moderate-sized islands, like Kahoolawe and Lanai, does not exclude recent subsidence; it may

FIG. 79

FIG. 80

FIG. 81

FIG. 79—Cliffed spur end, west coast of Oahu, between broad-floored valleys occupied in part by limestones. (Photograph by W. M. Davis.)

FIGS. 80, 81—La Pérouse Rock, French Frigate Shoal, northwestern Hawaii. (Photographs by Biological Survey, U. S. Dept. of Agriculture.)

simply exemplify the capacity of abrasion to undercut short valleys while slow subsidence is in progress.

The reasons for placing the larger Hawaiian islands in the marginal belt of the North Pacific are chiefly as follows: Most of them bear discontinuous sea-level fringing reefs; Oahu gives evidence of formerly more flourishing reef growth in its elevated limestone plains, thus indicating that ocean temperature has sometimes been more favorable for reef development in the past than now; also, the absence of a barrier-reef wall exterior to the recently emerged Oahu limestone plains or lagoon floors suggests that, for a time at least after their emergence, they were exposed to abrasion and hence that no living corals were then growing strongly on their margin. Furthermore, the absence of reef rims on the outer border of the banks around Oahu and other islands suggests that, in the earlier stages of the Postglacial rise of ocean level, corals could not thrive there; this is highly characteristic of the marginal belts in general.

The Northwestern Islets and Banks of the Hawaiian Chain

The generalized account here following of the 16 islands, banks, and reefs northwest of Niihau covers 1000 miles from southeast to northwest and is based upon "The Hawaiian Islands and the Islands, Rocks, and Shoals to the Westward," U. S. Hydrographic Office Publication No. 115, 2nd edit., 1903, pages 140–156, and on HO Charts 2 and 1216. Additional information concerning certain of the islands is contained in papers by Bryan (1903–07a), Elschner (1915), and Schauinsland (1899).

It should be noted at once that the members of the chain clearly fulfill the expectations deduced for the islands, banks, and reefs in the marginal belts of the coral seas. The chain includes five more or less imperfect bank atolls (Maro, Dowsett, Lisianski, Midway, and Kure), the reefs of which stand back from the bank margins; also eight banks, 10 or 20 miles across, from which no reefs rise to the surface. Three of the latter (Nihoa, Necker, and Gardner) have cliffed volcanic islets or stacks near their center; and five (no-name, Frost, Brooks, Gambia, and an 82-fathom bank) have neither bank reefs nor central rocks. One bank (French Frigate) is of intermediate character, as it has a cliffed central rock (Fig. 81) and a reef on one side near the bank margin. It would therefore seem as if the absence of reefs from these eight rimless banks must be because, as is to be expected in a marginal belt, a slight excess of unfavorable over favorable conditions has recently prevailed; in other words, because the Postglacial ocean temperature remained too low for reef growth until the ocean surface had nearly reached its normal level. Thus interpreted, the reefs are back-standing novices, except the far-northwestern Midway atoll, which apparently descends into deep water all around its 18 miles of circumference. It is curious that the opportunity for reef growth should

improve northwestward; witness the occurrence of surface reefs on the banks numbered 8, 10, (11?), 14, and 16 in northwestward sequence.

Second, the 12 reefs or banks from which no central rock rises must nevertheless be regarded as having volcanic bases like the four in which a small central rock survives; but in view of the great reduction or complete disappearance of the bases, all 16 of them must be classed as older than Kauai and as much older than Hawaii. This indicates a progressive southeastward shifting of volcanic activity in the Hawaiian chain, which has been long recognized as well assured. The fact that the banks that have no central rock are included among the nine northwestern members of the 16 examples accords well with this generalization; for the older the volcanic island, the more likely it is to have disappeared.

Third, it is reasonable to suppose that abrasion, probably low-level as well as normal abrasion, has been an effective means of promoting the reduction or disappearance of the basal volcanoes, for the cliffs of the surviving central rocks all plunge below present sea level. The southeasternmost two islands, Nihoa and Necker, still retain small uplands back of their cliffs; the other two, French Frigate and Gardner, are reduced to sharp stacks by the retreat of their cliffs so far that their inferred former uplands have been consumed. On the other hand, it is possible that subsidence also may have contributed to the disappearance of the volcanoes; and, when it is recalled that the two oldest volcanic masses in the larger southeastern islands, Kohala in Hawaii and Kaala in Oahu, exhibit evidence of having subsided, this possibility regarding the much older northwestern islands becomes a strong probability. Instability, thus inferred, is made the more likely by the occurrence of emerged strand lines at a small altitude on Nihoa and Necker islets, as reported by Elschner (1915).

Fourth, in view of the probability of subsidence, the banks, including those which do not bear reefs today, should be regarded as being only in part composed of abraded lava platforms and as largely composed of reef and lagoon limestones, built up to sea level during the subsidence of their foundations at times of favorable ocean temperature and cut away, probably by low-level abrasion, at epochs of unfavorable temperature. The latest epoch of low-level abrasion must have been of recent date; for, since it was closed by the rise of the ocean as a result of which the four central rocks now receive the attack of strong waves at normal level, no bench of significant width has been as yet cut around them. Such bench cutting in a plunging cliff face, where the detritus from the emerged part of the cliff falls into relatively quiet water, must of course be slow; but it nevertheless takes place, as is shown by the occurrence of small wall-and-bench notches cut at present sea level in the slanting face of the plunging cliffs of the Marquesas and other islands, as will be told later.

Fifth, if the preceding inferences are correct, it follows that intermittent abrasion, which has supposedly been applied chiefly at the lowered ocean level of the Glacial epochs, has been an effective aid to subsidence in reduc-

ing a number of volcanic cones or domes to islets and stacks in this region. This conclusion will have an important application when the barrier-reef islands and the almost-atoll islets of the coral seas are examined.

Sixth, the depths of the various rimless banks vary by small but significant amounts; and it is important to note that the variation is found not only at their outer margin but at their center also. The deepest is the 82-fathom bank beyond Midway island. French Frigate and Gardner both have depths near their central rocks of only 15 or 20 fathoms; Brooks and Gambia both have depths as small as 14 fathoms. The depths near Nihoa and Necker are still less.

Seventh, the central depth of banks with cliffed central rocks is less than the expected minimum depth of a platform cut by low-level abrasion, which according to Daly's calculations should be 30 or 40 fathoms. It may, of course, be argued that the level of abrasion would rise as the last Glacial epoch came to a close and that the cliff-base depth might therefore be less than the maximum measure of ocean lowering. But, if the moderate depth of plunging-cliff bases in a marginal belt is thus explained, it would seem impossible to explain central depths of 40 or 50 fathoms or more in large lagoons in the coral seas as the result of abrasion; for example, in the lagoon of Truk, the great almost-atoll in the Caroline group; of Tagula, surrounded by a superb barrier reef in the Louisiade group east of New Guinea; and of Macclesfield bank, apparently a drowned atoll, in the China Sea. It should therefore be concluded that, unless the calculated depth for low-level abrasion is too great, sediments must have accumulated around the cliffed central rocks of the Hawaiian banks in Postglacial time to a thickness of at least 10 or 20 fathoms; and if any subsidence has taken place in Postglacial time, the accumulated sediments would have to be thicker still. It should be noted that by far the greatest share of such sediments must here be of organic origin, for the central rocks are not only of small area but seem to be so little benched at present sea level that only an insignificant Postglacial contribution of inorganic sediments can have come from them. If it should prove that organic sediments can be supplied in so considerable a volume as is here inferred during so short a period as Postglacial time, then such sediments may be regarded as effective aids in aggrading not only lagoon floors but also submerged rimless banks in the coral seas and in maintaining their depth at a moderate measure, such as 40 fathoms, above which further aggradation with fine sediments may be prevented by wave action.

Eighth, it yet remains to mention what may be perhaps the most important lesson to be drawn from the long chain of banks; namely, the contrast that their frequent occurrence in the marginal belt presents to the scarcity of cliffed islands and shallow banks in the cooler seas of the North Pacific and other oceans. It is, to be sure, possible that no volcanic islands were ever formed in the more northern part of the Pacific ocean, for a similar freedom from islands and banks prevails in the marginal belt for

about 2000 miles to the east and to the west of the Hawaiian chain. Nevertheless, the absence of islands and banks, as far as now known, from the vast northern spaces of the ocean is very striking. It becomes still more striking when one recalls the occurrence of many atolls in the torrid Pacific. In any case the occurrence of abundant atolls in the Pacific coral seas, taken with the occurrence of several bank atolls and rimless banks in the Hawaiian portion of the marginal belt and with the extreme rarity of islands and banks in the cooler seas of the northern Pacific, must be regarded as highly significant. These facts are clearly much more accordant with Darwin's theory, modified by the action of low-level abrasion in the marginal belt, than with the Glacial-control theory.

Blank Spaces in the North Pacific Marginal Belt

A blank space of about 2000 miles occurs between Hawaii and North America. Westward from the Hawaiian islands is another blank space, lying between the northern tropic and latitude 30° N, free from islands for about 2000 miles, until the Bonin Islands are reached, to be described in the next section. It does not seem probable that many shallow banks are still to be discovered in these empty spaces, for they remain blank in spite of the discovery of the numerous banks in the northwestern part of the Hawaiian chain.

In this connection we may recall the occurrence of two submarine peaks between the California coast and Hawaii, as told in an earlier section. A similar peak with a summit depth of only 82 fathoms has been discovered 35 miles southwest of Midway island; it is described by Flint (1905) as rising 1269 fathoms in 1.8 sea miles and therefore having a gradient of 70 per cent.

Just north of the blank space west of the Hawaiian chain, Ganges island and a near-by rock reef are reported, 31° N, 154° E; but their existence is doubtful. An uncharted bank is reported at 30½° N, 157° E, with a depth of 34 fathoms but without indication of its extent. Two small islands, known as Los Jardines or Marshall, are reported at 21½° N, 151½° E; but their existence is doubted. Marcus or Weeks Island, HO 4, 24° N, 154° E, is a raised atoll about 2 miles in diameter, with its highest point 75 feet above sea level. As described by Bryan (1903–07) its outer slope has six beach lines, indicating intermittent emergence. It is surrounded by a sea-level fringing reef, outside of which is an unsurveyed bank. It is manifest that a close definition of the marginal belt in the North Pacific must remain impossible through most of its length by reason of lack of islands with which to limit it.

The Bonin Islands

The members of this group are all volcanic but, according to Yoshiwara (1902), are much older than the smaller islands on the north which lead to the Izu group, already described under the cooler seas of the North Pa-

cific. The independence of the Bonin Islands from that younger series of more northern islands is indicated by their standing somewhat to the east of its range. The above-cited author states that they are "typical submarine volcanoes," as they consist in part of tuffs containing Eocene nummulites, now uplifted to altitudes of 600 feet, as well as certain limestones originally formed as Miocene coral reefs and now uplifted to altitudes of 800 feet. Since then the islands, after having been further built up by

FIG. 82—Haha, in the Chichi group, Bonin Islands, south of Japan; HO 1902; five-fathom submarine contours are added.

volcanic eruptions, have been elaborately dissected and more or less submerged, as is told below.

The Bonin Islands, HO 5257, are divided into three sub-groups; the Muko or Parry Islands on the north, the Chichi or Beechey Islands in the middle, and the Haha, Coffin, or Bailey Islands on the south. The Muko or Parry Islands are shown only on the general chart, HO 5257, which lacks detail. They include half a dozen islets and rocks of irregular outline, the largest 1½ miles long, the loftiest 507 feet high, all rising from a single bank 30 by 10 miles, with marginal depths of 70 or 80 fathoms. This bank is separated by a narrow passage, somewhat over 100 fathoms deep, from the larger bank next south.

The Chichi Islands are, like the next subgroup, beautifully shown on a large-scale chart, HO 1902, reproduced from recent Japanese surveys, and here in part shown in Figure 82 with the addition of 5-fathom contours. They include several small islands and three larger ones: Ototo, 1 by 2½ miles, 766 feet high; Ani, 3 by 1½ miles, 831 feet high; and Chichi, 4 by 2 or 3 miles, 1072 feet high. The Haha subgroup includes one chief island of that name, in part shown in Figure 82, 7 by from 1 to 3½ miles, 1515 feet high; five smaller islands stand a few miles to the south. The

islands of both these subgroups are of irregular outline, Haha being almost of skeleton form; and their headlands are strongly cliffed. Few reefs are charted on their shores, but Darwin stated, on the authority of letters from Beechey, that at Port Lloyd, a bay on Peel or Chichi Island, "there is a great deal of coral; and the inner harbor is entirely formed of coral reefs, which extend outside the port along the coast," where "reefs fringing the island in all directions" are found; but he added: "At the same time it must be observed that the surf washes the volcanic rocks of the coast in the greater part of its circumference" (1842, p. 171). A member of the U. S. North Pacific Exploring Expedition reported the occurrence of a plain of coral rock adjoining the same bay a mile long, resting on trap rock, but the height of the plain is not recorded (Heine, 1856, Vol. 1, p. 294); and in the narrative of that expedition by Hawks it is said that the shore of the islands is "here and there edged with coral reefs" (1856, p. 231).

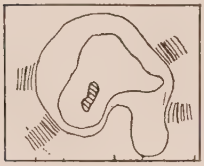


FIG. 83—Nishino, a residual islet and its bank, Chichi group, Bonin Islands, south of Japan.

All the members of the Chichi and Haha subgroups rise from a single bank which measures 63 miles north-south between latitudes 26½° and 27½°, with width of from 3 to 7 miles from the island shores to the bank margin, or a width of 10 or 12 miles over all. The greater part of the bank has depths of from 50 to 80 or 90 fathoms and falls off to deep water at about 120 fathoms. It is thus decidedly deeper than the Riu-kiu banks, next to be described; and it differs from them also in rising rather rapidly to a narrow and shallow bench around the islands. The base of the bench scarp lies at depths of 50, 60, or 70 fathoms and is apparently deeper on the east than on the west and deeper on the south than on the north. All this is strongly indicative of subsidence.

Nishino or Rosario Island, HO 1902, 70 miles west of the Chichi Islands, is a cliffed residual, ¼ mile long, 80 feet high. It rises from a bank 1½ miles across, with a well defined edge at the unusually small depth of 20 fathoms and a very rapid descent into deep water, as shown in Figure 83. Recent abrasion may be inferred here. Three active volcanic islands of small size stand 80, 110, and 130 miles south-southwest of the Bonin Islands: they are shown on insets of HO 1902, and all three appear to be cliffed with respect to present sea level. According to Yoshiwara, these three islands belong to the chain that leads northward to Fujiyama in Japan and are much younger than the Bonin Islands proper. On one of them, Yoshiwara says, "very young-looking reef-corals are now seen on the plateau about 300 feet above sea level" (1902, p. 302).

In the absence of detailed descriptions of the Bonin Islands, it is hazardous to state their physiographic history chiefly on the basis of their charts and their volcanic origin; but it appears safe to infer that, after earlier upheaval and erosion, the islands have suffered a considerable subsidence of recent date and rapid rate. This is inferred partly because the shore lines of their elaborately dissected masses are well embayed,

partly because the banks surrounding them have so great a depth. As to the latter point, be it noted that, if the shallow bench which rises from the bank near the Chichi and Haha Islands has been cut off in a scarp of low-level abrasion in the Glacial period, as seems entirely possible, some subsidence since that abrasion would be demanded, because the depth of the scarp base, 50 or 70 fathoms, is still, in spite of whatever sedimentation may have taken place since it was cut, too great to be accounted for only by the lowering of the Glacial ocean. Indeed, we may well believe that subsidence was in progress during abrasion, in order to account for the considerable difference of depth between the scarp base and the outer margin of the deeper bank.

The origin of the great mass of the deeper bank remains to be considered. In view of the absence of such banks around islands in the cooler seas and in view of the pronounced embayments of the Bonin Islands, the best explanation for the Bonin bank seems to be that it is essentially a reef-and-lagoon-floor terrace—a coral reef in the larger sense of the term—built up from a well dissected and rather rapidly subsiding foundation in past epochs of warmer climate and modified by abrasion and subsidence in epochs of cooler climate. Only in this way can the form of the islands and of the bank be accounted for.

Lest it seem extravagant to suppose that a bank so large as this one, which measures 63 by 12 miles, can represent a single barrier reef and its enclosed lagoon, the dimensions of several existing barrier reefs may be quoted. The superb barrier reef that surrounds Tagula and its satellites in the Louisiade Archipelago, east of New Guinea, measures 112 by 30 miles. The submerged barrier reef of Palawan, the southwesternmost member of the Philippines, is over 200 miles long. A partly submerged reef along the southern coast of eastern New Guinea is 350 miles long; another, also partly submerged, between Borneo and Celebes is nearly 300 miles long. New Caledonia, itself about 225 miles in length, is surrounded by a well developed barrier reef about 350 miles in length. The Great Barrier Reef of Australia is roughly 1000 miles in length. Hence, an oval barrier reef around the two subgroups of the Bonin Islands, measuring 63 miles in greatest diameter, would not have been of excessive dimensions in comparison with existing reefs.

The Riu-kiu Islands

The Riu-kiu, Lu-chu, or Nansei Islands, HO 5302, 5303, which stretch northeastward from Taiwan or Formosa toward Japan between 24° and 29° N, are chiefly composed of stratified rocks, and they lie near Asia instead of being mid-oceanic islands like most of those examined in this volume; they are nevertheless here included because they are pertinent witnesses to several aspects of our problem. They have fortunately been examined in some detail by Yoshiwara (1901) and by Yabe and Hanzawa (1923),

and they have been admirably surveyed by Japanese hydrographers; many of their charts have been republished by the U. S. Hydrographic Office. The general features of the islands thus appear to be as follows: Their stratified rocks have been deformed and greatly eroded; the sloping surfaces of the islands bear patches and covers of unconformable and elevated reef-limestone terraces of moderate thickness, more or less eroded, at various altitudes up to 690 feet above sea level. The shore lines of the less reef-covered islands are well embayed, and some of the inter-bay headlands are rather strongly cliffed. Most of the islands are bordered by fringing reefs, and a few are imperfectly fronted by bank-barrier reefs built on inferred platforms of abrasion. Nearly all the islands rise from broad, rimless banks of somewhat unlike depths.

The eroded island slopes manifestly dip below sea level, and the amount of subaerial erosion that the now submarine slopes of the embayments appear to have suffered seems to be, in view of the bay width, far greater than could have been accomplished during the lowered stands of the Glacial ocean. In view of this inference and of the above facts it is further inferred that, during a period of extensive erosion which began after the islands had been raised to a much greater emergence than now, they subsided intermittently and unequally to a greater submergence than now; and that while this subsidence was in progress the island shores were as a rule encircled and overlapped by unconformable reefs and lagoon limestones which prevented abrasion. It should also be noted that, as the elevated reefs are usually in the form of successive terraces each of moderate thickness, instead of in the form of a single reef of as great thickness as the height of the uppermost terrace—see Figure 19—the rate of subsidence must have frequently been greater than that of reef upgrowth. It is further inferred that, after a maximum subsidence, the reef-terraced islands were diversely upheaved, perhaps to a somewhat greater altitude than of today, and that additional reef terraces were formed during pauses in the upheaval; also that, after this upheaval and probably during a later subsidence, barrier reefs and their lagoon floors were for a time extensively developed until they gained the dimensions of the submarine banks that now generally surround the islands.

It is finally inferred that the outer reefs, on which the corals were weakened or inhibited by the Glacial lowering of ocean temperature, were thereupon more or less cut away by low-level abrasion, which in some cases reached and attacked the islands and cliffed their headlands; and that by reason of an insufficient rise of temperature in early Postglacial time, perhaps combined with local movements of subsidence while the ocean was rising to normal level, no new barrier reefs have grown up from the outer margin of the circuminsular banks; for the few reefs now found on the banks are bank barriers, rising some distance back of the bank margins although the ocean temperature is now high enough for fringing reefs to be well established around many of the islands.

The Riu-kiu islands would therefore seem to have recently suffered an interruption of protective reef growth, and some of them appear to have been cliffed in consequence; but they must have been reef-protected during the greater part of their earlier history, because their sea cliffs are so much less developed than their embayed valleys. Thus interpreted, these islands present features that are highly characteristic of the marginal belts of the coral seas. The growth of fringing reefs around most

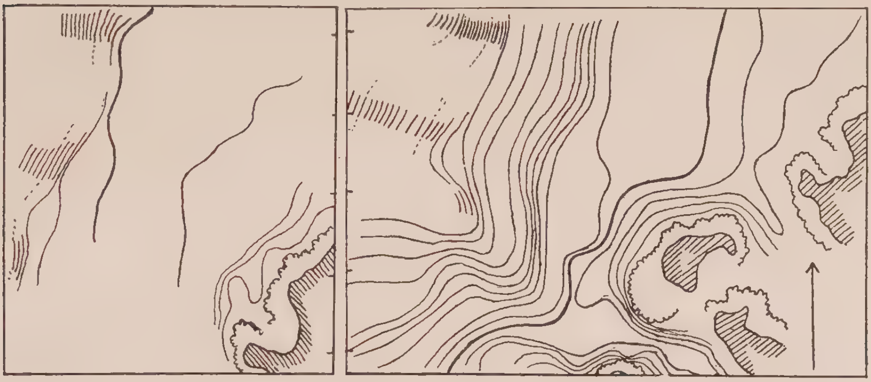


FIG. 84—Submarine contours, northwest coast of Iriomote, Riu-kiu Islands, southwest of Japan.

of the islands today has put a stop to their abrasion; but the warming of the ocean from a Glacial-epoch temperature that inhibited reef growth to a more genial temperature that now permits such growth seems to have taken place at too late a date for the development of true barrier reefs on the bank margins. In further support of the above inferences a few of the islands may now be briefly described, beginning on the southwest and following the facts of the charts and the geological report by Yoshiwara (1901). The terminations "shima" and "jima," meaning island, are omitted from the names.

Yonakuni, HO 5307, 6 by 2 miles, 757 feet high, consists of two islands of tilted sandstones united into one by flats of unconformable reef limestone about 30 feet in thickness; higher benches of limestone are found up to several hundred feet. Outside of a narrow and discontinuous fringing reef a bank 1 or 2 miles wide surrounds the island; it falls off irregularly into deep water.

Iriomote, HO 5307, 10 by 15 miles, 1449 feet high, has a steep bluff, like a modified fault scarp, along its non-embayed southern side, thus suggesting that the island is a tilted block. The bluff has a narrow fringing reef at its base, outside of which is a smooth bank, 5 miles wide, 20 fathoms deep near the fringing reef, and having a rapid marginal descent from depths of 40, 50, or 60 fathoms. On the northwest the island has a lower border with small flats of elevated reef, 30 or 40 feet thick, up to altitudes of over 100 feet. Here the shore line is strongly embayed between land arms and outlying islets; some of the embayments are narrow,

with depths of 45 fathoms one mile inland and 33 fathoms 2 miles inland: an exterior bank 2 or 3 miles wide falls off at 60 or 70 fathoms, as in Figure 84. The embayed valleys here demand a greater pre-erosional emergence, and the embayments demand a greater post-erosional submergence than can be provided by Glacial changes of ocean level.

Miyako, HO 5308, 12 by 8 miles, 378 feet high, is a characteristic member of the group. It is of unsymmetrical form, steep or cliffed on the southeast and sloping to the west like a tilted mass; the greater part of its surface is covered with reef limestone. The shore line is moderately irregular and is bordered by a discontinuous fringing reef ¼ or ½ mile wide. A bank 20 miles wide extends 10 miles to the north, with many scattered reefs rising from it; its depth close to the fringing reef of Miyako is about 20 fathoms; its marginal depth is 60 or 70 fathoms. A similar bank 2 or 3 miles wide lies on the south. The nearly level surface of the banks suggests that they have been formed, probably by abrasion and aggradation, after the uplift of the tilted island.

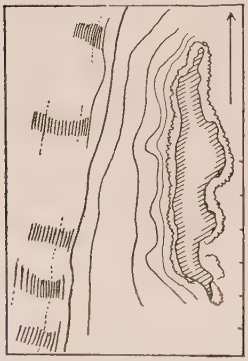


FIG. 85—Submarine contours, northern end of Okinawa group, Riu-kiu Islands, southwest of Japan.

Okinawa, HO 5303 and 2338, 60 by from 2 to 15 miles, 1496 feet high, the largest member of the Riu-kiu chain, consists of several original islands of irregular outline welded together by elevated reef limestones, which although of small thickness are found up to altitudes of 598 feet. Its bank has a rapid descent from 60 fathoms, as in Figure 85.

Amami, HO 5304, measures 30 by 15 miles; its height of 2293 feet is the greatest in the Riu-kiu islands. It bears only a few small and low patches of elevated reef near the northern end. It is maturely dissected and has a strongly embayed shore line with bold headlands, several of which on the west coast are 1000 or 1200 feet high, ½ mile or less back from the shore. Fringing reefs are best developed near the northern end of the east coast, where they are ½ mile wide. A bank from 5 to 8 miles wide surrounds the island; it frequently descends to depths of 40, 50, or 60 fathoms within ½ mile or 1 mile of the shore. Farther offshore the bank gradually descends to about 100 fathoms and then more rapidly to 200 or 300 fathoms.

Kakeroma, close to the southwest end of Amami, is represented in Figure 86. This is the finest example of a skeleton island in the group; it is 11 miles long by 5 in greatest width and is 1083 feet high. From its serrate axial ridge or backbone, narrow spurs project on both sides between open bays. No elevated reefs are reported on it. The spurs that descend into the narrow water passage between this island and Amami, like the Amami spurs on the other side of the passage, have a fairly rapid fall,

but they are not cut off in cliffs. On the other hand, the exposed spurs on the south side of Kakeroma, like those on the east and west sides of Amami, are rather strongly cliffed; one rises 719 feet and another 1048 feet at a distance of ¼ mile back from the shore. Discontinuous fringing reefs are seen up to ¼ mile wide.

The bank around Kakeroma is continuous with the Amami bank; it extends from 5 to 8 miles southward and has a fairly even surface at 70 or

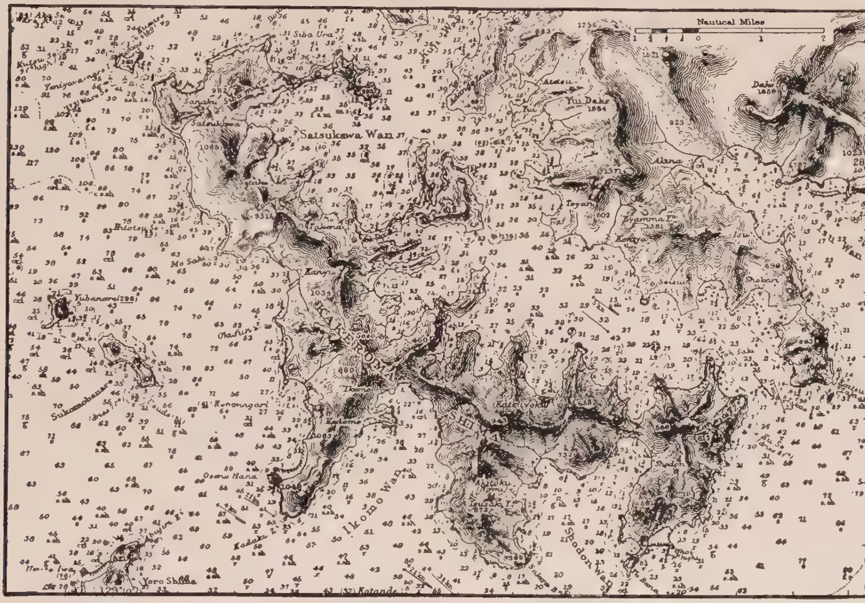


FIG. 86—The skeleton island of Kakeroma and its bank, Riu-kiu Islands; HO 3250.

80 fathoms; its fall-off of moderate declivity begins at about 100 fathoms. The depth of this bank is so great that it cannot have been abraded by the low-level Glacial ocean, unless it has since then subsided 20 fathoms or more.

Kikai, HO 5304, 12 miles east of Amami, 7 by 3 miles and 690 feet high, is covered with unconformable terraced reefs of moderate thickness up to its summit and thus has the greatest altitude of such reefs in the whole group. Inequality in movements of submergence and emergence is strikingly shown by the contrasts between Kikai and Amami. Kikai has no fringing reefs; it is surrounded by an irregular bank from 2 to 6 miles wide bearing three small ledges or reefs and having a fall-off at 60 or 70 fathoms. The remaining islands of the Riu-kiu arc, chiefly those of the Osumi group, are in the cooler seas.

The occurrence of a broad and muddy continental shelf along the neighboring coast of Asia appears to have prevented the formation of fringing reefs there, in spite of recent subsidence as indicated by its shore-line embayments. The same is true of that coast farther south in the coral seas, as will be told in a later chapter.

Evolution of Skeleton Islands

The Bonin and Riu-kiu groups present, in Chichi, Kakeroma, and certain other members, examples of embayed islands with skeleton outlines. They are characterized by a narrow and serrate axial ridge or backbone with slender lateral spurs or ribs; and the ribs enclose open bays. Islands of this kind in the Riu-kiu group are further marked by having their

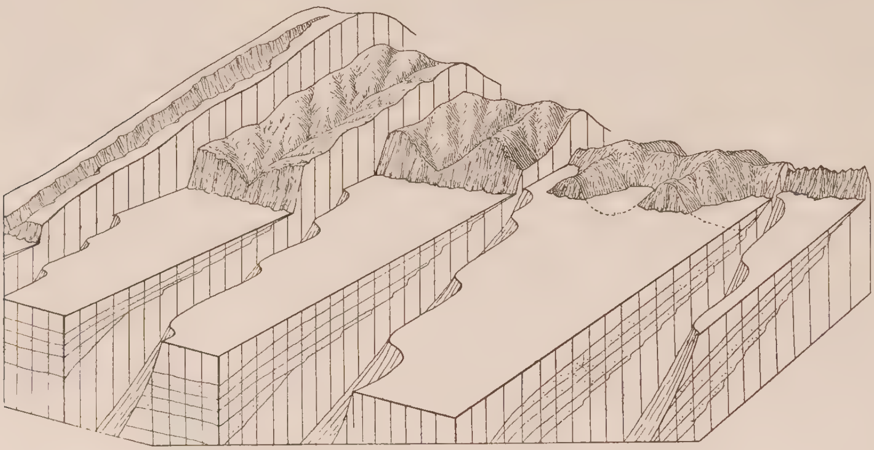


Fig. 87—Block diagram to illustrate the evolution of a skeleton island.

spur ends cliffed and by having shallow submarine banks of moderate width around them, as typified in the fourth block from the left in Figure 87. As far as my examination of charts goes, there are no islands of this kind exposed to open ocean waves in the cooler seas; they are occasionally found in the marginal belts of the coral seas, a few examples being described in my account of the Lesser Antilles (1926). They are not uncommon in the coral seas themselves. This fact alone raises the empirical presumption that their development demands the presence of protecting reefs during much of their history, and the presumption is supported by a deductive analysis of their features, as follows.

It has already been shown that well dissected and strongly cliffed but non-embayed islands, such as St. Helena in the South Atlantic, will be produced by erosion and abrasion in the cooler seas, if the islands remain stationary or subside slowly; also that the production of well embayed islands in the cooler seas, like Banks Peninsula of New Zealand, seems to demand a relatively rapid subsidence for a time at least, after abrasion and erosion are well advanced. The production of a skeleton island in the cooler seas would seem to require a similarly rapid subsidence after erosion is still further advanced; indeed advanced so far that all the valley heads have opened into amphitheaters, leaving only narrow ridges between them; and to require also that the original dimensions of the island should be so large that abrasion shall not have been able to reduce it to a small

cliffed residual during the long and slow progress of its advanced erosional sculpture. If any such island existed there it ought to be surrounded by a rather wide and deep bank. The absence of such islands from the cooler seas can hardly be because none are old enough to have suffered advanced erosional and abrasional sculpture, as in the third block of Figure 87, before a rapid subsidence gave them a skeleton outline; for Deserta, in the Madeira group of the Atlantic, has reached the serrated residual stage of the fifth block: hence the absence of skeleton islands from the cooler seas must more probably be because none have suffered the proper succession of changes. The production of a skeleton island in the coral seas is easily explained by the association of long continued erosion with slow subsidence, as in the second and third blocks of Figure 87 except for their cliffs, and later with rapid subsidence, as in the fourth block; protection from abrasion being all the while afforded by encircling reefs. Such islands should have tapering spur ends: they exist in fair number. The production of a skeleton island in a marginal belt of the coral seas is also easily explained under the same conditions, excepting that protection by encircling reefs must be temporarily withdrawn in a late stage of island evolution in order that the inter-bay spur ends should be more or less strongly truncated. The Waianae range of Oahu would make a fine skeleton island if it were more submerged.

The skeleton islands above described are believed to exemplify the third scheme of development just outlined; and as such they serve as competent witnesses to the existence of a marginal belt in which reef protection has long been prevalent, although temporarily removed after erosion had become well advanced.

The South Pacific Marginal Belt

Islands between Australia and New Zealand

Norfolk Island, HO 1982, 13 square miles in area and 1050 feet in height, stands northwest of New Zealand. As described by Carne (1885) and Laing (1913), the exposed part of its coast rises in wall-like cliffs from 200 to 400 feet in height, but they are lower or wanting on the southwest: there the smaller Philip Island stands 3 miles away, with cliffs 900 feet high on its exposed side. Along the lower side of Norfolk Island is a small fringing coral reef. The uplands of the island are deeply furrowed with ravines, from the hanging mouths of which the streams cascade down the cliff face into the sea. Soundings of 12 or 14 fathoms near certain cliffs suggest that they plunge below sea level. Both islands stand on a vast bank, measuring 60 miles north and south by 20 east and west and therefore somewhat smaller than the Bonin bank south of Japan and only about half the length of the great barrier-reef lagoon floor which surrounds the Louisiade island of Tagula. The bank is 20 fathoms deep near the island and 40 or 50 fathoms deep around its margin.

Lord Howe Island, HO 2014 (Fig. 88), 1 by 5 miles, 2840 feet high, stands between Norfolk Island and Australia in latitude 31½° S. It has been described by Hill (1869), Etheridge (1889), and Oliver (1916): the latter observer regards it as "a fragment of a once more extensive area; sheer cliffs of 800 feet show sections of horizontal lava flows testifying to a vast amount of denudation." A fringing reef follows much of the west coast. The island and some islets to the north surmount a bank measuring 15 by 20 miles; the bank depths near the shore, about 20 fathoms (Fig. 90), suggest that the islands are cut off in plunging cliffs. The bank-margin depths are 40 or 50 fathoms.

Not far away is the gigantic volcanic stack known as Balls Pyramid, HO 2014 (Fig. 89), ½ by ½ mile, with its extraordinary height of 1816 feet ex-

FIG. 90—Submarine contours, bank east of Lord Howe Island; HO 2014. Crosses show soundings.

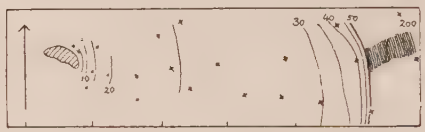


FIG. 91—Submarine contours, bank around Balls Pyramid; HO 2014.

ceeding its smaller sea-level diameter. Four plunging-cliff islets stand half a mile to the west. They all surmount a bank 10 miles across, with near-shore depths of 15 or 20 fathoms and marginal depths of 40 or 50 fathoms (Fig. 91). This is probably the highest pelagic stack in the world.

Middleton and Elizabeth reefs, between Norfolk Island and Australia in latitudes 29° and 30° S, HO 2015, are small bank atolls, both about 4½ by 3 miles, with lagoons 6 fathoms or less in depth. The second should not be confused with Elizabeth Island, an elevated atoll near the Paumotus. Submarine banks extend around the reefs for half a mile or a mile, before pitching down at 40 or 45 fathoms to deep water. All these islands and reefs exhibit typical marginal-belt features.

EVOLUTION OF STRONGLY CLIFFED ISLANDS IN THE MARGINAL BELTS

Low-level abrasion in the Glacial epochs must have been a very active process if it were wholly responsible for the cliffing of the three above-named volcanic islands. Perhaps a good beginning of cliff cutting was accomplished in their reefless youth, and aid to later abrasion was probably given by subsidence. The great Norfolk Island bank probably represents the site of several volcanoes, all but one of which, and that presumably the largest, are now completely removed by abrasion and subsidence. In any case, these strongly cliffed marginal-belt islands appear to differ in two respects from the skeleton islands of the Bonin and Riu-kiu groups above described. They have probably been exposed to low-level abrasion for a larger share of several Glacial epochs, and they have prob-

Fig. [illegible].—The [illegible] at Lord Howe Island, between Australia and New Zealand. (Photograph from Dept. of Mines, Sydney, N. S. W.)

FIG. 89—Balls Pyramid, between Australia and New Zealand, a volcanic stack 1816 feet high. (Photograph from Dept. of Mines, Sydney, N. S. W.)

ably subsided more slowly than the skeleton islands. The contrast presented by these two classes of islands is interesting in showing how large a variety of island forms is consistent with the scheme of the marginal belts.

As in the case of a number of other banks already described, the recurrence here of a marginal depth of 40 or 50 fathoms is more suggestive of an aggradational adjustment of the bank surface to wave action at normal ocean level than of abrasion at a lowered ocean level. The position of these islands between Australia and New Zealand makes it probable that they have subsided, independent of any evidence for subsidence that they themselves offer; for both the insular continent on the west and the continental island on the east have lost some of their former area by marginal downwarping.

FIG. 92—Submarine contours, bank north of Raoul Island, Kermadec group; BA 167.

The Marginal Belt on the East Coast of Australia

Before tracing the marginal belt across the South Pacific, its position on the northeast or Queensland coast of Australia must be examined. The southern end of the Great Barrier Reef, which might be expected to mark the place where the marginal belt impinges on the continent, is found to lie in latitude 24° or 25°, several hundred miles farther north than the Middleton and Elizabeth bank atolls just described. Its end is determined by a northward drift of beach sand which there prevails and which has produced two offshore sand reefs, 60 and 70 miles in length, which will be described more fully in Chapter XIII. It is therefore probable that the end of the great reef today is defined more by sand-reef encroachment than by water temperature. Agassiz has given an illuminating account of the contest here going on between reef-building corals and beach-building sands, which will be quoted when the Great Barrier Reef is described in the account of the Pacific coral seas. The marginal belt of the coral seas is therefore not well defined on the Queensland coast.

Islands between New Zealand and South America

Raoul or Sunday Island, the chief and northernmost member of the Kermadec group, 29° S, 178° W, HO 2001, about 3 by 6 miles across, and 1632 feet high, is of embayed and somewhat stellate outline, with cliffed headlands rising 500 or 1000 feet above the sea. It is surrounded by a bank up to 3 miles in width, on the northeast part of which stand several cliffed islets, known as the Herald Islands. The bank (Fig. 92) is mostly 15 to 30 fathoms deep, but its margin is not well defined by soundings.

The following banks and rocks are placed in the marginal belt chiefly because of their latitude, the banks around them being of undetermined extent: La Brilliante, a "small bank," 24° S, 170° E, 30 fathoms deep;

Pelorus bank, 23° S, 176½° W, of undefined area, 14 to 19 fathoms deep; Haymet rocks, 27° S, 160° W, awash, ¼ mile across, no bank reported, and of uncertain position; Fabert shoal, 24° S, 158° W, known only by a single sounding of 68 fathoms; Orne bank, 27½° S, 157½° W, probably 8 or 10 miles across, with soundings of 16, 34, 35, and 68 fathoms; Neilson or Lancaster reef, 27° S, 146° W, a submerged reef, 6 by 1 miles, showing "white coral" at depths of from 2 to 20 fathoms; President Thiers bank, 24½° S, 146° W, 6 miles across, 19 to 21 fathoms deep, showing "corals and shells."

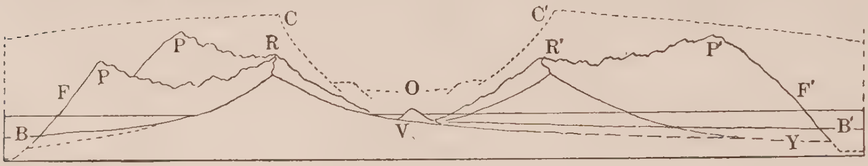


FIG. 93—Diagrammatic cross section of Rapa Island, South Pacific. (Based on a drawing by L. J. Chubb.)

Rapa, HO 2011, 27½° S, 144° W, 4½ miles across, 2077 feet high, is, according to a lately published account and section by L. J. Chubb of London, who has recently visited the island, the residual of a much larger caldera-form volcanic mass. It has been greatly dissected by its shorter inflowing and its longer outflowing consequent streams, strongly cut back by abrasion around its exterior slope, and then well submerged, so that its valleys are now embayed and its cliffs are partly drowned. A recent emergence of six or eight feet is indicated by a narrow shore bench. Fringing reefs are imperfectly developed.

The chief bay, entering from the east, is believed to occupy a valley, *CVY*, Figure 93, cut down beneath the original caldera floor by a stream which discharged all the centripetal drainage of the in-sloping caldera slopes, *COC'*, and which presumably found its way out through an original breach in the caldera wall. The exterior or centrifugal streams appear to have cut down their valley heads, *R*, *R'*, much below the inferred initial height of the caldera rim, *C*, *C'*; perhaps by reason of the divergence of these valleys from the island center toward its margin, the inter-valley ridges increase in height outwards. Their highest peaks, *P*, *P'*, are near their cliffed ends, *F*, *F'*. The breadth of the drowned-valley bays taken with the steepness of the valley sides suggests a considerable depth of erosion while the island stood higher than now; and yet the streams are so short that their valleys must have then had hanging mouths above the cliff-base platform of abrasion. The subsidence of the island has therefore probably been decidedly greater than the depth of the circuminsular bank, *B*, *B'*.

The island is surrounded by a 30-fathom bank that is shown by soundings to be at least a mile wide and that, judging from the moderate dip of the lava beds in the radial spurs and from the height of the spur peaks, is probably wider still. The bank is presumably more or less

aggraded on a well submerged rock platform of abrasion. Chubb suggests that the platform may be at one point six miles wide, without including the exterior detrital embankment. So wide a platform must have been abraded, at least in part, during the Preglacial youth of the island, when reef growth was prevented by outwashed detritus.

Maretiri, 50 miles east-southeast of Rapa, consists of four islets, 2 miles over all, 346 feet high, with abrupt shores and shallow soundings on a bank at least a mile wide but without good definition of the edge of the bank. Again according to Chubb, these islets probably represent the dissected and partly submerged caldera rim of a single volcanic island. Portland bank, 23½° S, 134½° W, is 7 by 2 or 3 miles across with soundings of 15 fathoms, more or less. Next come two young volcanic islands: Pitcairn, of forlorn history, HO 1977, 1 by 3 miles, 1000 feet high, of simple outline with ragged shore cliffs and a mile-wide bank to the northwest and northeast, 20 or 30 fathoms deep at the margin, and no charted coral reefs; and Easter or Rapa-nui, HO 1119, 27° S, 109½° W, 9 miles across, 1767 feet high, with low shore cliffs and no embayments, surrounded by a shoal 30 fathoms deep a mile offshore but without definition of margin. This island has been recently well described with respect to its archeology by Mrs. Routledge (1920).

Sala-y-Gomez, HO 1119, 26½° S, 105½° W, consists of two masses of rock about ⅕ and 1/10 of a mile across, joined by a narrow isthmus; depths of 35 to 45 fathoms are charted for a mile around. A mile to the east lies Scott reef, 100 yards long but not specified as to its composition. It is manifest that, compared with Norfolk, Lord Howe, Raoul, and Rapa islands, these last-named islands, rocks, and banks are not, as now known, very informing witnesses; but, in view of the absence of banks to the south, the number of them found here is significant. No safe conclusion can be reached as to the limits of the Pacific marginal belts until its islands and banks are better explored.

The Marginal Belt in the Eastern Pacific

The Marquesas Islands

It has already been remarked that the cooler seas of the North and South Pacific unite in the eastern part of the ocean and that the Galápagos Islands on the equator appear to be kept almost free from coral reefs by the great volume of cool water brought there in the Humboldt Current. Westward from these islands a vast blank space extends for over 3000 miles before the Marquesas Islands are reached. In earlier papers (1918b, p. 406; 1920a, p. 217; 1921) I have treated these islands as belonging in the coral seas and as being free from reefs today by reason of recent and rapid submergence. I now propose, in spite of the occurrence of the almost-atoll of Clipperton Rock far to the northeast and of the abundant Paumotu atolls several hundred miles to the south—all these

belonging in the coral seas—to place the Marquesas in what may be called the eastern marginal belt of the Pacific, where the northern and southern marginal belts are inferred to run together across the equator. This may be done, if on no other grounds, in order to give the islands the benefit of a double consideration; but a special reason for it is found in the small size of some of the cliffed members of the group. For, on the as-

FIG. 94—Atuana bay, south coast of Hiva Oa. (Drawn from photograph by J. P. Iddings.)

sumption adopted in my earlier papers that ocean temperature hereabouts is high enough for reef growth, it should be only the relatively good-sized members of the group that could have furnished enough outwashed stream detritus to prevent the formation of reefs and to permit cliff cutting. The fact that some of the smaller islands are now hardly more than cliffed stacks strongly suggests that not an abundance of detritus but a deficiency of temperature may have been the cause of failure of reef protection at the time when the now-plunging cliffs were cut. On the other hand, the absence of reefs may be due in large part to the absence of coral larvae in the ocean current that approaches the Marquesas group from the east, for the water temperature here prevailing is but little lower than that of other islands where reefs are flourishing.

The Marquesas group, HO 1797, 8° to 10° S, 138° to 140° W, includes 11 larger islands up to 10 or 15 miles across and from 2000 to 4000 feet high, besides many smaller ones. All are of volcanic origin; all are strongly cliffed, and all the larger ones appear to have been well dissected before their recent submergence, so that they now have many moderate-sized embayments, partly occupied by beach-fronted deltas, between their cliffed headlands. But some of the bays may have been produced by the

downfaulting of island segments, as is perhaps the case on Hiva Oa (Fig. 94). Back of the bay-head deltas the embayed valleys appear to rise rapidly into the interior, and their rock floors therefore presumably fall but little less rapidly below sea level to their original mouths now submerged. The battered cliffs of the headlands plunge boldly into the sea, and depths of from 12 to 20 fathoms are found a short distance offshore. Photographs taken by the late J. P. Iddings in 1912 and by representatives of the American Museum of Natural History a little later show that in some of the headlands, flat, narrow, discontinuous benches backed by vertical walls of moderate height are cut into the slanting faces of the much higher headland cliffs, apparently in sine-and-cosine relation. The benches are slightly emerged, and the emergence may be due to the lowering of ocean level inferred by Daly for the Samoan and other islands. Evidently the valleys were eroded chiefly during the same reef-free period of greater emergence as that which witnessed the abrasion of the now-plunging cliffs. No data are available from which close estimates of the present rock-bed depth of the valley mouths can be made; but the fall of the valleys appears to be so steep that their submerged mouths may well lie from 50 to 70 fathoms or more below present sea level. No coral reefs occur, although coral fragments are found on the bay-head beaches. The late Dr. A. G. Mayor, who visited these islands with Agassiz in one of his trans-Pacific voyages, told me that individual corals are seen growing on the submerged cliff faces, thus representing the embryonic stage of fringing-reef growth that I later saw on a cliffed lava headland of the island of Ambrym in the New Hebrides.

The scanty descriptions of the Marquesas islands by all but the latest of the many explorers and travelers who have visited them leave much to be told concerning their physiographic history and its bearings on the coral reef problem. Their striking forms have impressed many voyagers. Melville describes them as having "bold, rock-bound coasts, with the surf beating high against the lofty cliffs, and broken here and there into deep inlets [embayments], which open to the view thickly wooded valleys, separated by the spurs of mountains clothed with grass, and sweeping down to the sea from an elevated and furrowed interior" (1846, p. 13). Other general accounts are given by Stewart (1831), Hutton (1874), Stevenson (1896), Christian (1910), and Handy (1923).

Agassiz (1903a, pp. 1–5) briefly notes that some of the islands have "uniform lava slopes reaching from the central backbone" and that the slopes and the coast line clearly indicate "the immense amount of erosion to which the . . . islands have been subjected." All along the southern coast of Nuku Hiva, one of the larger islands, "one follows a huge, lofty, nearly vertical wall, . . . broken into by the deep valleys facing the bays and harbors; . . . numerous waterfalls dropping . . . into the sea from 2000 feet." Nevertheless this widely experienced observer saw "no indications" that the Marquesas had "been subjected to the effect of sub-

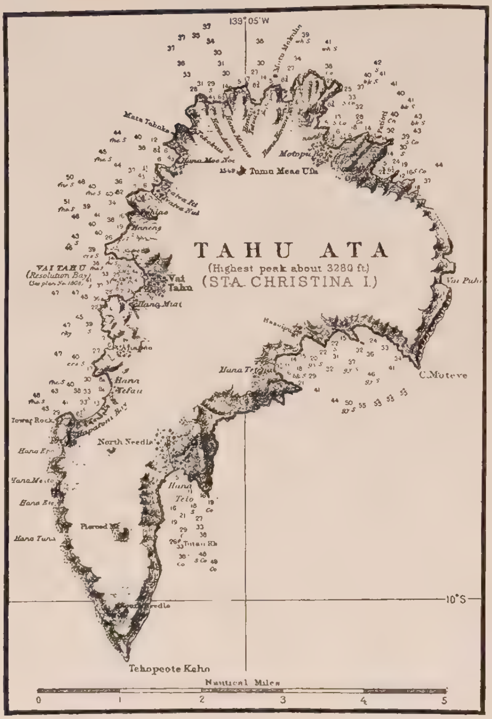


FIG. 95

FIG. 96

FIG. 95—Tahu Ata, Marquesas Islands; HO 1599.

FIG. 96—East end of Hiva Oa, Marquesas Islands; HO 1599.

sidence." His explanation of the absence of reefs is found in the "fact that there have been no great platforms of erosion formed at the base of the slopes" (1903a, p. 4); and he later adds: "The absence of a shore platform on . . . the Marquesas is probably due to the steepness of the slopes, which, when cut into, do not form the wide level platform characteristic of other Society Islands" (1903a, pp. 140–141). He thus overlooked the evidence for the occurrence of rather broad submerged platforms given by the very cliffs whose height and steepness he noted. Dana, on the other hand, while also failing to note the probable occurrence of submerged platforms, recognized the evidence for submergence given by the island embayments and suggested that "the Marquesas may . . . have once had barrier reefs, which were sunk from too rapid submergence; and afterwards, on the cessation of the subsidence, others failed to grow again on account of the deeper waters" (1849, p. 138).

The broad, abraded platforms, which must be inferred to extend seaward from the submerged bases of the high, plunging cliffs, have presumably been more or less aggraded with or without the aid of reef growth during and since their submergence; but

with a few exceptions the resulting banks are not yet demonstrated by soundings. Only for the island of Tahu Ata or Tau-ata, HO 1599 (Fig. 95), 7 by 2 to 4 miles, 3280 feet high, are soundings numerous enough to show the existence of a well defined bank around the greater part of the island circuit, with margin at a depth of about 40 fathoms before greater depths are reached. The soundings in a bay near the east end of Hiva Oa, HO 1599 (Fig. 96), suggest that a platform exists all around its plunging-cliff shore. The Pacific Pilot states (p. 187) that all around the island of Ua Huka, 7½ by 5 miles, "there are said to be depths of from 22 to 25 fathoms at distances varying between ½ mile and 2 miles from the shore." Also, that the south coast of Nuku Hiva "has, within 1 mile of the shore, depths of from 35 to 50 fathoms over a fine sandy bottom" (p. 189). Again, that Motu Iti and some near-by islets are "surrounded by a bank of muddy sand and coral, on which as little as 15 or 20 fathoms is found 2 miles from the shore" (p. 195). Regarding Nuku Hiva, some recent, unpublished soundings made by the U. S. Cruiser *Trenton* to the west of the island give depths of 2000, 124, 24, and 19 fathoms at distances of 21, 18, 15, and 12 miles, thus clearly suggesting the existence of a broad bank with a rapid descent to deep water. Hence, although the existence of similar circuminsular banks around the other islands, where soundings are few or wanting, is at present only a matter of inference, the inference is probably correct. In so far as the bank margins lie at about 40 fathoms, their depth is more probably an indication of adjustment of aggrading processes to normal sea level than a measure of submergence. The small bench-and-wall notches, above mentioned, that have been cut in the cliff faces appear to stand in cosine-and-sine relation to the cliff-face slant; and this suggests that the present attitude of the islands was rapidly assumed. But before safe conclusions can be reached on these various points the islands must be critically studied with various alternative explanations of their origin in mind.

A Later Interpretation of the Marquesas Islands

Since the foregoing summary was written, a physiographic interpretation of these islands by Chubb (1925), their latest scientific visitor, has come to hand; and, although it does not cover all members of the group, it easily supersedes all earlier accounts and calls for a highly significant addition to the conclusions above stated. The two islands concerning which Chubb reaches generalizations are Nuku Hiva and Hiva Oa. They both exhibit somewhat even highlands at a considerable altitude above sea level. It was at first inferred that their eruptive growth was followed, while they stood decidedly lower than now, by a stationary period long enough for their peneplanation over extensive areas, although some high ridges still survived; but a personal letter from this observer, of later date than his brief published report, informs me that he inclines to explain the summit highlands of these two islands as platforms of incomplete abrasion. In view of what is known regarding volcanic islands in the cooler

seas, it must be believed that an unprotected island would be cut away by abrasion before it could be worn down to a peneplain by subaerial erosion: hence the second of these two explanations seems the more probable. The truncated masses were elevated and deeply dissected; and the valleys then eroded have been later embayed by submergence, leaving the surfaces of truncation at altitudes of 2500 and 1500 feet. Nothing is said of the contemporary abrasion of the present sea cliffs: they were evidently not cut in a youthful stage of the island's history but in a youthful stage of the post-truncation emergence. The almost complete absence of coral reefs is ascribed to the restricted number of genera of corals living there and is therefore looked upon as having "an ecological rather than a geological significance"; but to this it may be added that the restriction in the number of coral genera is probably of geological significance, as a consequence of the temperature of the Postglacial epoch.

The Marginal Belt of the South Indian Ocean

The small number of islands in the Indian Ocean about latitudes 20° to 24° S make the definition of its marginal belt very uncertain. On the eastern side of the ocean, where the equatorward flow of a relatively cool current might be expected to restrict coral growth, the Horstman Abrolhos Islands, HO 3422, composed of coralliferous limestones, stand in the surprisingly high latitude of 28° S, 40 miles from the Australian coast, and near but not on the edge of the continental shelf where it falls off from 30 or 40 fathoms to much greater depths. They are therefore bank reefs. About 120 miles farther north the shelf has a similar width, but its edge has a depth of 70 or 80 fathoms. As described by Dakin (1918–22) the Abrolhos (Portuguese for "Open Your Eyes") consist of small masses of eroded coral limestone up to 30 feet in height, with dunes rising somewhat higher; each island is surrounded with flats of worn-down limestones bordered with fringing reefs. A recent smaller elevation is indicated by a bench eight feet above sea level. The islands might therefore be regarded as representing a former bank atoll, uplifted and now in process of degradational transformation into a new sea-level atoll in the manner proposed by Agassiz (1899, p. 135).

A blank oceanic space of some 2000 miles must be crossed before the islands of Rodriguez, Mauritius, and Réunion are reached in the region east of Madagascar, about 20° S. All three of these islands present certain features that correspond to some of those found in the islands of the Pacific marginal belts; that is, Rodriguez and Mauritius are adjoined by banks from which no marginal reefs rise to sea level, and Réunion is cliffed without reefs. But in view of their latitude and still more in view of the fact that a number of other banks without marginal reefs are found still nearer the equator in this ocean, thus suggesting that recent and rapid subsidence rather than an insufficient Postglacial rise of tempera-

ture has determined the absence of marginal reefs, and of the further fact that Réunion is a relatively young cliffed island and not the greatly reduced remnant of an ancient island, these three islands will be later described under the coral seas of the Indian Ocean.

Madagascar

The great subcontinental island of Madagascar appears to stretch from the coral seas of the Indian Ocean across the marginal belt into the cooler seas. It is a mountainous mass, 800 miles in length and 250 in breadth, with a relatively rapid slope to the reefless east coast, to be described later, and a more gradual descent to the west. A brief account of its cliffed and reefless southern end in latitude 26° S has already been presented. On the west coast a narrow and more or less discontinuous fringing reef begins in latitude 25° S and is replaced by a narrow bank barrier, two miles off shore, about latitude 22° S. This is referred to by Darwin, who stated that a harbor "is formed by a narrow reef ten miles long, extending parallel to the shore, with from four to ten fathoms within it. If this reef had been more extensive, it must have been classed as a barrier reef; but as the line of coast falls inward [turns eastward?] here, a submarine bank perhaps extends parallel to the shore, which has offered a foundation for the growth of the coral" (1842, p. 187; also p. 102). Soundings of later date show this surmise to be correct; hence, in spite of its relatively low latitude, this part of the coast of Madagascar may be tentatively placed in the marginal belt. The uncertainty in the case comes from the continuation of the submarine shelf with increasing width and with only discontinuous bank reefs for a considerable distance farther north, as will be told when Madagascar is again referred to in the account of reefless coasts of the coral seas in Chapter IX.

The Marginal Belt of the Atlantic Ocean

From what has been said of the broad extension of the Atlantic cooler seas across the equator, and also from what is known of the occurrence of coral reefs in the West Indies but not in corresponding latitudes along the Argentine coast, it must be inferred that the coral seas of this ocean have a greater extension in the northern than in the southern hemisphere. The marginal belt may therefore be described as following a curved path, convex eastward, from the middle coast of Brazil where the reefs of Parcel das Paredes stand on the continental shelf, around Cape San Roque and through the Lesser Antilles toward Florida, but on the way making a long northeastward loop to take in the isolated reefs of Bermuda. Unfortunately the number of islands included in much of this long course is small, and the location of the marginal belt is therefore uncertain over great distances.

Reefs near the Coast of Brazil

The reefs of the Parcel das Paredes, about 18° S, HO 1672, may be taken as marking in a general way the district where the marginal belt reaches the coast of South America south of the equator. The possible inclusion of the Trinidad "coral" rocks, 20½° S, 29½° W, in the marginal belt has been noted in the account of the cooler seas of the Atlantic. The transit of the belt across the equator is marked by two islands, Fernando Noronha and the Rocas. The first of these, HO 537, 4½ by 1½ miles, 1000 feet high, has irregular shores and outlying rocks, with headland cliffs of moderate height. Darwin described the island as of volcanic origin and suggested that "denudation has here been effected on an enormous scale" (1844, p. 23). A shoal extends a mile to the north and northwest, with 36 fathoms of water. Buchanan recorded that some of the smaller outlying islets are "partly or wholly composed of calcareous sandstone" (1876, p. 613). Branner stated (1903) that no coral reefs occur here, although a few corals are to be seen on the rock faces, and water-worn coral fragments are found on the beaches. The failure of reef growth may be due largely to the lack of supply of coral larvae in the equatorial current, which comes from the reefless cooler seas of the North and South Atlantic.

The reef of the Rocas was long ago described by Lieut. S. P. Lee of the U. S. Navy, who examined it about 1850 (1854). It appears to be a slightly emerged bank atoll, the only one of its kind in the open Atlantic, about 1½ miles in diameter, enclosing a small lagoon and surmounting a shallow bank which extends several miles seaward. Two small islands lie on the western part of the reef flat; it is elsewhere interrupted by many fissures and holes and carries more than 20 "black rocks"—possibly of volcanic origin but more probably weathered limestone—from 10 to 15 feet high and up to 50 feet across; one has a breadth of over 200 feet. As blocks of such a size can hardly have been thrown up by the surf from the reef face, they may perhaps represent the last remnants of an uplifted and eroded reef. On the surrounding bank, depths of 15 fathoms were found 6 miles to the northeast and of from 15 to 18 fathoms 2 miles to the northwest. The margin of the bank is not defined. Its small depth gives support to the suggestion that a recent elevation has taken place. The absence of barrier reefs on the outer margin of the banks around these two equatorial islands places them in the marginal belt.

The 900-mile stretch of the low and island-free coast of northeastern South America is swept by a strong northwestward branch of the equatorial current and is fronted by a continental shelf consisting of muddy deposits supposed to be largely derived from the Amazon and having no coral reefs.

The Lesser Antilles

This chain of islands, HO 2319, 2318, is the only one in the Atlantic which resembles the several insular festoons that border the coast of Asia in the Pacific. It extends 500 miles northward and northwestward between the continental island of Trinidad near the Venezuelan coast and Porto Rico, the first member of the Greater Antilles, and includes 25 larger members with an uncounted number of smaller ones.

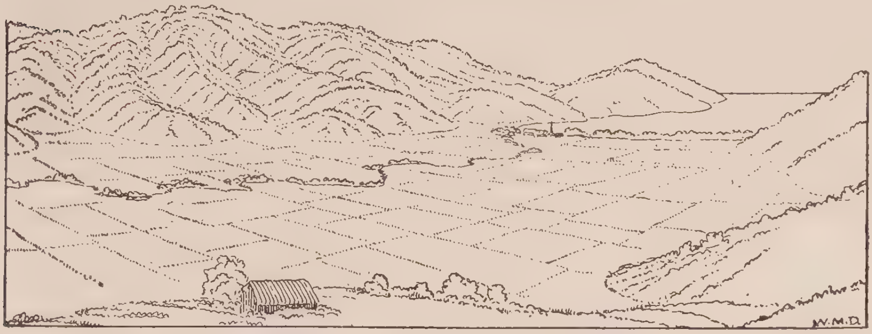


Fig. 97—A delta plain filling a drowned-valley embayment, west coast of St. Lucia, Lesser Antilles.

Fig. 98—Mountain spurs cut off by plunging cliffs, southwest coast of Martinique, Lesser Antilles.

I have already published a shorter (1924a) and a longer (1926) account of this insular chain, based on my visit of 1923, when its members were found to present the typical features of marginal-belt islands. The volcanic slopes of the older islands are maturely dissected, the resulting valleys are well embayed, and the bays are partly delta-filled, as in Figure 97, the inter-bay spurs are cut off in immature plunging cliffs, Figure 98, the abrasion of which must have required a much shorter time than the erosion of the valleys. Hence during the greater part of the valley-erosion period the islands must have been protected from abrasion by encircling reefs; and these reefs were presumably offshore barriers, whose upgrowth accompanied the subsidence by which the valleys were embayed. But today no such reefs exist: they must have been cut away in an early stage of an epoch of Glacial or low-level abrasion which later witnessed the cliffing of the island spur ends. The resulting low-level platforms, cut partly across reef and lagoon-floor limestones and partly in the volcanic rocks of the sloping spurs, are now aggraded by an

unknown thickness of Postglacial deposits, mostly of organic origin, with near-shore depths of 10 or 15 fathoms and marginal depths of about 40 fathoms, as if in adjustment with normal oceanic processes. Discontinuous bank reefs rise to smaller depths but seldom reach the sea surface.

A gratifying result of my examination of these islands was the discovery that, with the exception of the aberrant island of Barbados, they might be arranged in genetic sequences, in which slow subsidence has long been the dominating control of the progressive changes of form and of reef upgrowth and in which low-level abrasion during the Glacial period was a temporary and subordinate control. A simple sequence begins with a young volcanic cone and ends with a sea-level atoll. A more complicated sequence begins again with a volcanic cone and advances to a normal barrier-reef or atoll stage, and then after uplift enters a second cycle of subsidence which in some instances again advances to a barrier-reef stage. Marie Galante, an evenly uplifted atoll, is at the beginning of a second cycle. All members of the chain were instructive, but none so much so as Antigua, the climax of a complicated sequence. This island, initially of volcanic origin, appears to have subsided several thousand feet and thus to have reached the atoll stage of its first cycle in middle or late Tertiary time; it was then uptilted and eroded during a second cycle to a surface of moderate or low relief which, truncating its tilted structures, reveals them admirably; but during the post-tilting erosion it again subsided and became reef-encircled a second time. It was this barrier reef of second-cycle upgrowth that was cut away to a platform by low-level abrasion, which also cliffed the island spur ends, as I have elsewhere told (1924). The platform is now aggraded and bears imperfect bank reefs.

It is a peculiar merit of a successful theory that it brings order out of confusion by providing for many apparently independent items of observation a systematic arrangement in a well coördinated whole. When such a theory has been framed the facts that pertain to it are no longer seen only as so many isolated individual occurrences; on the contrary, they fall into their proper relative positions so naturally, become the essential elements of a reasonable entity so spontaneously, and in those positions support each other so helpfully that one wonders why they ever seemed unrelated to one another. Yet a period of five months elapsed after my visit before the coördinated meaning of the Lesser Antillean Islands was perceived. Since then, the islands, banks, and reefs have seemed almost transparent, so great has been the aid given by the adopted view of their origin in penetrating their structures and in recognizing the past conditions and processes through which they were brought into being.

Divergent Interpretations of the Lesser Antilles Reefs

Important earlier studies of West Indian coral reefs have been made by Vaughan, who, after publishing a number of shorter articles about them

from 1913 to 1916, summarized his results in two detailed reports (1917, 1919). His interpretations of the Lesser Antillean banks and reefs are in several respects different from those presented on the preceding pages of this volume. The differences appear to arise in part from his substantial rejection of Darwin's theory, which, when supplemented by low-level abrasion in the marginal belts, is in my view as admirably successful here as elsewhere; and in part from his inattention to the special conditions of the marginal belts of the coral seas, which seem to me of capital importance in the present connection.

On one point, however, we agree; namely that the Lesser Antillean reefs are based upon platforms in whose production the present reefs took no part; but this partial agreement is immediately followed by disagreement. Vaughan takes the conditions under which the Lesser Antillean reefs were formed to be typical of the conditions under which the great barrier reefs of the Pacific were formed; while my view is that the Lesser Antillean reefs are mere timid, Postglacial novices belonging in the marginal belt of the Atlantic and therefore properly comparable only with similar novices in the Pacific marginal belts; for they are very unlike the vigorous veteran barriers of the Pacific coral seas. Furthermore, Vaughan apparently excludes coral reefs of earlier date from all share in the production of the platforms on which the Postglacial novices of the Lesser Antilles are based, and he carries this exclusion into an explanation of platforms which he assumes to exist beneath the veteran reefs of the Pacific coral seas. My view makes the earlier Lesser Antillean reefs essential factors in the production of the great, terrace-like, circuminsular masses which were in Preglacial time inherently similar to the great terrace-like masses that today surround the barrier-reef islands of the Pacific coral seas; for both appear to have been formed during the slow subsidence of their insular foundations by the upgrowth of their reefs, associated with the infilling of the enclosed lagoons and the external addition of long, downsloping talus deposits.

Vaughan's rejection of Darwin's theory is indicated by several statements concerning submarine platforms of small depth from which both Atlantic and Pacific reefs are believed to have grown up in moderate thickness; and also from certain more explicit expressions which discredit the scheme of reef development in the manner that Darwin's theory suggests. Thus it is said that "no evidence has as yet been presented to show that any barrier reef began to form as a fringing reef on a sloping shore and was converted into a barrier by subsidence; but it is clear that many, if not all, barrier reefs stand on marginal [corrected by the author to read "stand on or margin"] platforms which already existed previous to Recent submergence and the formation of the modern reefs. . . ." It would thus appear that, inasmuch as Recent submergence is explained at least in part by Postglacial ocean rise, neither island subsidence nor reef upgrowth is held to be of importance.

Nevertheless, in a chapter giving "an account of the American Tertiary, Pleistocene, and Recent coral reefs," Vaughan has presented by far the most compelling evidence ever published regarding the formation of many such reefs in association with the subsidence of their basis. Thus, among the Tertiary reefs preserved in the coastal-plain strata of the southeastern United States, one at Bainbridge, "rests on the surface of the upper Eocene Ocala limestone, which shows evidence of subaerial erosion" (1919, p. 265). Several reefs of later dates but of similar structural relations are described; like the first they are local structures of small thickness, resting unconformably on a widespread series of nearly horizontal strata. In view of their unconformable superposition, it is concluded that "with possibly one exception each [reef] development occurred during subsidence which followed subaerial erosion" (1919, p. 268); and it had been earlier said that in Florida "every conspicuous development of coral reefs or of reef corals took place during subsidence" (1915, p. 59; see also 1919, pp. 268, 271).

Descriptions are also given of a number of uplifted Tertiary reefs in the West Indies. Here, however, inasmuch as the submarine slopes of the islands descend into deep water, it may be well believed that the conditions of reef formation were significantly different from those afforded on the broad continental shelf of the southeastern United States. The following pertinent passages may be extracted. On Antigua an Oligocene reef is said to have an unconformable contact with "a basement that had been subaerially eroded and was later depressed below sea level"; the overlying limestones, hundreds of feet in total thickness, are interpreted as having been "deposited in shoal water on a flattish floor" (1919, p. 260), thus implying a continuation of the subsidence that introduced reef growth. An upper Oligocene reef of Anguilla "was evidently formed during submergence after the subaerial erosion of its basement" (p. 262). It is added that all these fossil reefs "were formed during periods of subsidence that followed subaerial erosion of their basements . . . four of the six . . . are buried under later nearly pure limestones in which there are few or no corals" (p. 263). These overlying pure limestones might, it would seem, be interpreted as reef-enclosed lagoon deposits, although that possibility is not noted.

In view of the explicit recognition thus given to the growth of Lesser Antillean coral reefs on subsiding insular foundations in Tertiary time, it is not clear why such coral reefs should be almost as explicitly excluded from all share in the production of the circuminsular platforms on which the present bank reefs are based; yet such exclusion appears to be indicated by various passages. For example: "An examination of the barrier reef platforms of Florida, Andros Island, Bahamas, Cuba, and Australia all lead to the same conclusion, viz.: (1) The platforms have an existence independent of coral reefs and were formed by other than coral reef agencies; (2) the reefs exist only on those portions of the platforms where the

conditions requisite for the life of reef-corals prevail" (1914d, pp. 32, 33; also 1916, p. 45).

In comment upon these statements I can only urge that, in so far as the Lesser Antillean as well as other marginal-belt islands are concerned, reef upgrowth and lagoon infilling on subsiding foundations seem to me to be eminently possible processes for the production of great terrace-like masses, which may then be changed into circuminsular platforms by low-level abrasion; indeed, these processes of platform production around such islands seem to me so much more probable than any others that I have adopted them as giving a valid explanation of platform origin. Five lines of evidence may be summarized in substantiation of this view.

First, the presence of coral reefs in Tertiary time during the formation of the platform masses around Lesser Antillean islands which have not been uplifted is sufficiently proved by the occurrence of fossil reefs on neighboring islands—Barbados always excepted—which have been uplifted. Vaughan has shown (1919, pp. 259–263) that uplifted Eocene reefs are found on St. Bartholomew; Middle Oligocene reefs on Antigua, Porto Rico, and Cuba; Upper Oligocene on Anguilla; Miocene, meagerly, on Cuba and Santo Domingo; and Pleistocene on Cuba and Jamaica. If no uplifted reefs of Miocene, Pliocene, or Pleistocene dates are yet found on the Lesser Antilles that probably means that whatever reefs were then formed there are still submerged. The general presence of reefs in Tertiary and later time is also shown by the absence of strong spur-end cliffs on the various islands. Second, the subsidence of the Lesser Antillean islands is indicated by various facts presented in my account of those islands (1926); and that their subsidence has been slow may be presumed from the occurrence of extensive submarine terrace-like masses which have been built up around the non-uplifted islands, and even more safely from the structure of earlier-made, submarine, terrace-like masses on the uplifted islands; for in these the structure of their former terrace-like masses is now open to observation by reason of their uplift and erosional dissection. Third, barrier reefs may be reasonably regarded as having been formed by upgrowth from fringing reefs on the slopes of subsiding islands, in view of the features of various islands which such reefs encircle in the Pacific coral seas, as will be shown later in some detail. Such an origin for the uplifted barrier reef of Mangaia in the Cook group, described in Chapter XV, has recently been demonstrated by Marshall in the clearest manner. Fourth, lagoon infilling during Tertiary reef upgrowth may be well accepted as an effective process, whatever the source of the material, in view of the abundance of calcareous detritus that has accumulated in Postglacial time on various Lesser Antillean banks, after the platforms had been smoothed off there by the action of low-level abrasion on preëxistent circuminsular terrace-like masses. The evidence of this accumulation is found not only in the moderate marginal depths of most of the banks but also in the beaches that now stretch in concave curves between cliffed

headlands of volcanic rocks; for the beaches consist almost wholly of in-swept calcareous sands. At present, while the banks are not rimmed with reefs, a considerable share of the bank detritus must be "wasted" by being swept off into deep water; but, while Preglacial reefs were present, less detritus would have been swept away and a larger proportion of it would have been used to aggrade the enclosed lagoon floors. Fifth, low-level abrasion must have recently acted for a relatively short time to transform great, barrier-reef, terrace-like masses into circuminsular platforms; for the reefs, which must have long protected the islands from abrasion while they were undergoing long continued erosion, are now absent. The presence of immature plunging cliffs on the island headlands between the maturely opened, embayed valleys leads to the same conclusion.

It is believed that these several lines of evidence lead to the interpretation of the Lesser Antilles as marginal-belt islands and also that the lines of evidence are well enough argued to show that the interpretation has not been adopted hastily or without good warrant. On the other hand, it is fully recognized that the theoretical elements of the interpretation are only figments of the imagination, because the conditions and processes of the past inevitably lie beyond the reach of observation. The theory has therefore no such secure foundation as the facts. It may be wrong.

The Outlying Island of Bermuda

Bermuda, HO 27, a narrow, straggling island, 13 miles long, 210 feet high, may be classed as a special case of bank-atoll formation. It consists, as described by Nelson (1837), Jones (1859), Rein (1870), Heilprin (1889), and Agassiz (1895), of eolian deposits from beaches of calcareous sand. The island surmounts an imperfect bank atoll, 20 by 10 or 12 miles in extent, enclosing a lagoon 5 or 10 fathoms deep, and surrounded by an exterior bank from 2 to 4 miles wide with a marginal depth of 30 or 40 fathoms. Two smaller rimless banks lie 10 and 20 miles to the southwest: Challenger bank, 5 miles in diameter and 30 or 40 fathoms deep, and Argus bank, 6 miles in diameter and from 20 to 35 fathoms deep. Rapid descent is made from all three banks to depths of 1000 or 2000 fathoms.

It should be recalled that, after an examination of this island half a century ago, Rein conceived the idea that non-subsiding banks of a considerable depth might be built up toward the ocean surface by the accumulation of pelagic organic deposits so that reef-building corals could eventually grow up on them and form atolls. He thought that this process was to be preferred as being simpler and more natural than reef upgrowth from subsiding foundations; and he very illogically concluded that the subsidence of Bermuda in particular was improbable "because the neighboring coasts of America and Africa show emerged formations" (1870, p. 81).

Interest in the origin of Bermuda has recently been revived by the discovery, as reported by Pirsson (1914), of a volcanic foundation beneath

the limestone cover in a well that is said to have been bored in the wild hope of securing an artesian water supply from the American coast! Volcanic rocks were encountered at a depth of 245 feet below sea level and were penetrated for 1033 feet to a total depth of 1278 feet below sea level, or 1413 feet below the island surface where the boring was made. It is to be regretted that the word "platform" was used in the title and text of Pirsson's paper and that the submarine volcanic mass was represented in his diagram with an evenly truncated summit; for, though the truncation of a moderate-sized island by low-level abrasion is eminently possible in the marginal belts, and especially on their polar sides, there is in the case of Bermuda no sufficient warrant for such truncation as long as the depth of only a single point in the contact surface between the volcanic foundation and the limestone superstructure is known. Moreover, Pirsson's text gives little consideration to the possibility of subsidence and even assumes stability to be more probable than instability, yet without consideration of the fact that practically every volcanic island in the coral seas which bears uplifted reef limestones must, in view of the unconformable contact of the limestones on their foundation, have subsided before it was elevated. The occurrence of waterworn pebbles and sand in the Bermuda boring at 565 feet, and of "a bed of sand . . . which had been worn upon a beach" between 910 and 940 feet, would at least suggest subsidence after eruption and erosion; but they were not so interpreted. Finally, the present depth of the assumed volcanic platform, or 245 feet, is taken to indicate a rise of ocean level rather than a sinking of the supposedly truncated cone.

Pirsson's general statement is as follows: "Provided we believe in the permanence of the deep ocean basins, it is clear that volcanoes situated on their floors, after they had been cut down to sea-level, if they once projected above it, would be protected from further erosion and would remain indefinitely as protuberant masses. . . . It appears to the writer that what has been learned regarding the history of the Bermuda volcano has an important bearing on the question of the way in which the platforms on which coral islands, barrier reefs and atolls are situated, have been formed. . . . Provided the volcanic masses are of sufficient antiquity they may, even though of great size, have been reduced to sea level, furnishing platforms of wide extent. . . . Such masses . . . would continue to project from the ocean abysses indefinitely and many of them may be of great geologic age. There is nothing in the mere size of any of the atolls of the Pacific which would preclude their being placed on the stumps of former volcanic masses." This conclusion is not satisfactory because it takes the existence of sub-reef platforms for granted and because it takes no account of two important matters. One is that platforms like the one assumed to exist under the Bermuda limestones are practically unknown even in the Pacific cooler seas where the truncation of volcanic islands would be unimpeded. The other is that practically all barrier-reef and almost-atoll

islands favor the assumption of instability and subsidence of volcanic islands rather than that of their stability.

Vaughan's interpretation of the history of Bermuda, based on an examination of the limestones that cover the volcanic foundation, leads to a different conclusion (1919, p. 295). Following Cushman's identifications, the lowest fossils from the boring, coming from oxidized volcanic material at depths between 250 and 350 feet below sea level, are taken to be probably of Eocene age, and the volcanic eruption is therefore dated as Eocene or Pre-Eocene. The limestones are regarded as having been deposited during Tertiary and Pleistocene time; and, as some of them are of shallow-water origin, it is inferred that subsidence accompanied and followed their deposition.

In the present connection it is not so much the total history of the Bermuda foundation as the relation of the limestones and atoll reefs to the bank which they surmount that demands attention. An emergence of probably more than 100 feet is generally believed to have been associated with the accumulation of the eolian limestones; hence, at the time of their accumulation nearly all the now submerged bank must have been laid bare; its area would have been 230 square miles. A later submergence brought about a reduction to the present area of 19 square miles. It seems eminently possible that this emergence and submergence, as well as the truncation of the bank, were associated with late Glacial changes of ocean level. Whatever has been the behavior of the volcanic foundation and however the bank was formed upon it, the incompetence of recent corals to build a strong atoll rim around the bank border proclaims that Bermuda lies in the marginal belt of the Atlantic. Its out-of-the-way position would appear to be explained by the exceptional warmth of the Gulf Stream, and its bank would appear to represent the remains of a former atoll of vigorous growth in a Preglacial period of higher temperature than now. The atoll was presumably abraded by the lowered Glacial ocean, and its stump was more or less aggraded in Postglacial time. Hence, as stated above, Bermuda should be classed as an imperfect bank atoll, heaped up with wind-blown sands on part of its circuit.

Marginal-Belt Reefs of Florida and the Gulf of Mexico

The offshore reefs of southern Florida, CS 1248–1252, are here regarded as bank barriers belonging in the marginal belt of the Atlantic, because they frequently fail to reach the sea surface and because a good number of them do not stand close to the steep pitch by which their bank descends into deep water. They have been described by L. Agassiz (1852) and E. B. Hunt (1863) but more completely by A. Agassiz (1883) and Vaughan (1914). The latter observer in particular has given them well-considered treatment as local elements in the geological history of their region. It was from an examination of these reefs that Le Conte was led (1857) to suggest that offshore barrier reefs might be formed without subsidence by

upgrowth from a shelving sea floor, thus unconsciously repeating Darwin's idea of the same kind.

The northernmost living reefs are at Fowey Rocks, latitude 25½°; the city of Miami is on the mainland a little to the northwest. The farther northward extension of the reefs is restricted by a southward drift of siliceous sands, long known to the officials of the Coast Survey. Special attention was called to this drift by Shaler in an account of the Florida coral reefs (1890). The southward drift of the sand seems to be largely due to longshore currents acting in conjunction with waves, the currents being parts of several backset eddies which work in gear with the Gulf Stream offshore. It will be shown in a later chapter on the barrier reefs of the coral seas that the southern extension of the Great Barrier Reef of Australia is restricted in a similar manner by a northward drift of shore sands, as Agassiz was the first to point out.

According to Vaughan, the growth of the living reefs of southern Florida has been associated with the subsidence of a preëxistent floor of sedimentary deposits. This sub-reef "platform is independent of corals and . . . owes its existence to agencies other than those dependent upon the presence of coral reefs. . . . The platform on which the present barrier reef of Florida is growing has . . . stood 30 feet or more higher, and has been brought to its present position by depression" (1914d, pp. 27, 30). Back of the living reefs is a belt of slightly elevated Pleistocene reefs, 105 feet thick where bored through, which constitute a discontinuous sequence of keys, now followed and connected by the Florida East Coast Railway for 100 miles; the Key Largo limestone—so named after the largest key—of which these reefs are composed resembles the rock of the present reefs and is thought by Vaughan to have been formed under similar conditions; that is during or after a subsidence which followed the uplift that closed Pliocene deposition in this district (1914d, p. 30).

How far the subsidence and uplift here inferred may be replaced by a rise and a fall of ocean level in association with a late Glacial epoch, it is at present impossible to say; but it is easily conceivable that the Pleistocene reef, formed during one or more Interglacial epochs of normal ocean level and relatively high temperature, was cut back during a late Glacial epoch of lowered ocean level and temperature and that the present reef was built up in Postglacial time on the abraded platform thus prepared. In view of what has elsewhere been learned regarding the abrasion of marginal-belt reefs in the Glacial epochs, it is reasonable to think that something of the same kind took place here also.

Beyond and to the west of the end of the discontinuous keys or the remnants of Pleistocene reefs, are two reef patches known as the Marquesas and the Tortugas. They both stand well back from the margin of a broad and shallow bank. The Marquesas have the appearance of a bank atoll. A. Agassiz wrote of the Tortugas: "They form the most recent of the cluster of Florida reefs, and have not as yet been transformed into the normal

coral reef" (1888, Vol. 1, p. 58; also p. 109). He regarded them as shoals formed by current-drifted detritus, on which corals had begun to grow when the shoals had been built up to a sufficiently small depth (1883; 1888, p. 58). According to Vaughan's preliminary studies both the Marquesas and the Tortugas are mostly composed of "organic detritus and calcareous material drifted westward along [near?] the southern margin of the Floridian bank" (1910, p. 181). After a more detailed study of "the Marquesas and Tortugas atolls," the same observer later wrote: "The atoll rings are constructional phenomena and were shaped by prevailing currents"; that is by currents which follow the Florida keys southward and westward, thus running counter to and with less strength and regularity than the Gulf Stream. The rings consist largely of drifted detrital material, which is chiefly of coral origin in the Tortugas but not in the Marquesas (1914c, p. 62). The lagoon deposits back of the Florida reefs have been found by Vaughan to be almost exclusively formed of locally deposited oolitic limestone; calcareous detritus derived from the enclosing reefs is almost negligible in comparison.

It is unfortunate for the coral reef problem that the Marquesas and Tortugas were ever called "atolls"; for neither in structure, situation, nor origin have they any close resemblance to the typical atolls of the Pacific. They do not even exemplify the kind of atoll which Darwin suggested as possibly based upon banks or shoals of whatever origin; for their reefs, in so far as they have any, are not situated on the margin of a bank overhanging deep water. Nor do the Marquesas and the Tortugas closely resemble the lagoon atolls of New Caledonia and Australia, for there local reef growth appears to be of essential importance as compared with detritus drifted from some other source. These Florida pseudo-atolls give no aid in the study of Pacific atolls; indeed, they may hinder that study, in so far as ideas gained in Florida are applied to mid-Pacific reefs. It would almost seem that Agassiz, not recognizing the evidence for slight subsidence which Vaughan later discovered as conditioning the growth of the Florida reefs, had here early conceived an antipathy to the association of island subsidence with the upgrowth of barrier and atoll reefs; for, in the accounts of his wide experience with such reefs in the Pacific, subsidence was excluded in practically every case, in spite of the varied evidences which testify for it.

The shelving bottom of muddy sediments on the west coast of Florida appears to be as ill adapted to the growth of corals as is the similar bottom of the Sunda Sea in the Dutch East Indies or the shoals off the delta of Fly River south of mid-New Guinea. Thence westward, the Gulf of Mexico is free from reefs and banks across its middle; but small patches of bank reefs, characteristic of the marginal belt, are found on the Mexican continental shelf near Vera Cruz, HO 2606; they have been described by Heilprin, who briefly summarized their features as follows: "The reefs of the Vera Cruz waters consist of a number of detached islands or banks, from

less than half a mile to one and a half miles in length, which extend eastward from the coast line for a distance of nearly six miles. . . . A second series of reefs begins about eight miles to the southeast" (1890, p. 308). The isolation and discontinuity of these reefs as well as their retreat from the edge of the continental shelf, thus leaving a considerable breadth of shallow water outside of them, suffices to distinguish them from the stalwart reefs of the true coral seas.

Summary for the Marginal Belts

The preceding survey of the marginal belts in the Pacific, Indian, and Atlantic Oceans leads to several novel results. First, the belts certainly exist, although their boundaries are regrettably indefinite over broad oceanic regions, because of the absence of islands. Second, the embayed islands in these belts give good evidence of instability with prevalent subsidence; the islands that bear elevated reef limestones also testify for instability. Among these, Oahu is a strong witness for subsidence which, before a recent elevation of small measure, was in progress even during the eruptive growth of its younger volcanic dome. Third, the cliffed islands and stacks give no direct evidence of subsidence, but the presence of banks around them as well as around the embayed and the limestone-bearing islands, while similar banks are practically wanting in the cooler seas, leads to the belief that the banks represent great, terrace-like, coral reef masses, formed by reef upgrowth and lagoon infilling during the subsidence of their foundations and recently modified in a superficial and subordinate manner by low-level abrasion in the Glacial epochs and by aggradation in Postglacial time.

Fourth, the cliffs by which the marginal-belt islands are so generally characterized show clearly that the low-level abrasion to which the cliffs are due was not similarly operative in the coral seas, where, except on a small number of young volcanic islands, cliffed shores are wanting. Fifth, it is disappointing to find that in these marginal belts, precisely where low-level abrasion acted most effectively, the level at which it acted cannot be determined, chiefly because of the Postglacial aggradation of the platforms that it is believed to have produced and partly because of possible Postglacial changes of island level. Sixth, inasmuch as the bank atolls of the marginal belts are believed to crown islands that have been more or less abraded in the course of their subsidence, they may differ from the typical atolls of the coral seas in having, beneath their banks, moderate-sized platforms of volcanic rocks instead of the rounded mountain tops such as are supposed, according to the subsidence theory, to occur under atoll lagoon floors in the coral seas. Marcus atoll, being a slightly emerged bank atoll in the marginal belt of the North Pacific, would seem to offer a good opportunity for boring through its limestone cover in order to learn the nature and form of its foundation; but the results disclosed by such

a boring should not be taken to hold good for the atolls of the true coral seas.

The islands, reefs, and banks of the Pacific marginal belts may be summarized more specifically as follows: The Hawaiian section of the northern belt contains, apart from the larger islands, of which Oahu is the most instructive, several plunging-cliff islands, surrounded by shallow banks; also three banks without islands or reefs; three normal atolls; four bank atolls; and one deep bank of 82 fathoms. Far to the west it contains a good number of embayed, cliffed, and bank-surrounded islands in the Bonin and Riu-kiu groups. The southern belt contains in its western part two small bank atolls; two larger plunging cliff islands, Norfolk and Lord Howe, and a smaller one, Balls Pyramid; farther east, two embayed islands with cliffed headlands and surrounding banks; two young islands; and a number of ill-defined rocks and banks. Where the two belts join in a cross-equator belt in the eastern Pacific, it is thought to contain the Marquesas Islands, first worn down or truncated, then uplifted, deeply dissected and strongly cliffed, finally well-embayed as if by subsidence; submerged platforms corresponding to the cliffs are believed to surround the islands; reefs are wanting. It is hoped that observation of these islands in future will give special attention to the peculiar marginal-belt features that appear to characterize them.

The single marginal belt of the South Indian Ocean is vaguely defined by reason of the absence of islands on its path; and even the great island of Madagascar, which evidently lies athwart its course, does not clearly delimit it.

The discovery of the very unsymmetrical course of the Atlantic marginal belt is one of the most surprising results of the present study. The course of the belt was altogether unexpected, yet it seems to be well certified in spite of the aberrant case of Barbados, the reconciliation of which with its neighbors must be regretfully left to the future. The persistence and consistence of marginal-belt features along the chain of the Lesser Antilles in the Atlantic are as striking as they are along the northwestern extension of the Hawaiian chain in the Pacific; indeed, these two chains of islands and banks constitute, each for its own ocean, the best evidence yet obtained for the verity of the marginal belts as essential subdivisions of the oceans with respect to the development of coral reefs. If islands were elsewhere as plentiful as in these two chains, the course of the marginal belts might be rather sharply defined instead of remaining as indefinite as it now is across wide, island-free stretches of ocean.

The study of the Atlantic marginal belt in its course through the Lesser Antilles has been particularly gratifying in several respects. Each member of that island chain proves to be worthy of special investigation for itself alone, because divers problems of eruption and erosion, of emergence and submergence, of reef growth and reef abrasion are more or less completely represented there. But each member gains an added interest when

a comparison of all shows them to exemplify various stages of development in a simple but comprehensive scheme of island evolution. And, when the island chain as a whole comes thus to be understood, it is found to have a still larger value because it is so clearly characterized by certain peculiar features found to characterize also the islands in the marginal belts of the Pacific; namely, features that indicate, first, a continuance of successful reef growth on subsiding islands in Preglacial time; second, a relatively short-lived inhibition of reef growth with resultant low-level abrasion in the Glacial epochs; and third, a more or less successful revival of reef upgrowth in Postglacial time. Thus the Atlantic marginal belt, best represented by the Lesser Antillean islands, stands between the cooler seas of the Atlantic, where coral reefs have never grown even in the warmer non-Glacial epochs, and the warmer seas of the American mediterraneans, where coral reefs have long flourished even during the cooler Glacial epochs. The Lesser Antilles thus take their place in a world-wide problem and, in doing so, give confirmation to the conclusions that had been previously reached independently for the marginal belts of the Pacific.

Thus understood, the marginal belts not only add a most interesting complexity to the coral reef problem of Darwin's time; they provide also a most salutary correction for the excesses of the Glacial-control theory. The cliffed islands of the marginal belts truly validate the occurrence of low-level abrasion, as postulated in that theory, and thus substantiate the most significant process by which the study of coral reefs has been enlarged since the subsidence theory was formulated. But the cliffed islands at the same time restrict the area over which such abrasion has acted, and many of them discredit the associated postulate of insular stability by which the Glacial-control theory is unfortunately limited.

It is certainly significant that the islands and banks here described verify the expectations deduced in Chapter VI regarding subsiding islands in a marginal belt where reef growth has been alternately favored and inhibited in the Glacial period. And it is no less significant that the circuminsular banks of these cliffed islands, the like of which are practically absent from the cooler seas, become relatively prevalent as soon as a climatic boundary is crossed. This fact, not previously considered in the study of coral reefs, is believed to give strong support to Darwin's theory of upgrowing reefs on subsiding foundations, subordinately modified by the addition of changes of ocean level and temperature and therefore by changes in the marginal belts from reef growth to reef death as proposed in the Glacial-control theory.

It may be noted in conclusion that the breadth of the marginal belt in the North Pacific, where it is best defined, suggests that the temperature of the last Glacial epoch was about 8° or 9° F. (4° or 5° C.) lower than at present. This agrees well with estimates based on altogether different evidence in other regions.

CHAPTER IX

REEFLESS COASTS IN THE CORAL SEAS

Object of Inquiry

The survey of the cooler seas and of the marginal belts of the coral seas having now been completed, we may turn to our main area of study, the coral seas themselves, with respect to which all the preceding pages have been preparatory. These seas will be found to contain a great variety of islands and reefs, which must be divided into groups; and each group must be treated separately. For the purpose of completeness, reefless coasts as well as reef-bordered coasts will be here included, beginning with reefless large-island and continental coasts of emergence, and continuing with large-island and continental coasts of submergence which, although sometimes having discontinuous fringing reefs, are not fronted by barrier reefs. Next will come young and reefless or nearly reefless volcanic islands without indications of subsidence; and these will be followed by dissected and embayed volcanic islands either bordered by fringing reefs or encircled by barrier reefs. Almost-atolls will then be treated; but next, instead of atolls, elevated reefs of various kinds will be taken up in order that the evidence furnished by them as to their origin may be compared with that furnished by sea-level barrier and almost-atoll reefs. Drowned atolls and rimless submarine banks will follow. Sea-level atolls will be treated last, because they are the most problematic elements of our subject.

Petrography, Biology, and Physiography in the Coral Reef Problem

It may occasion surprise, not to say disappointment, on the part of some readers of this book that, although it is largely concerned with coral reefs, it nowhere contains the learned names by which to identify the members of the extraordinary symbiotic assemblages repeatedly seen on reef slopes and in lagoon waters; and also that, although frequent mention is made of volcanic islands, no use is made of the elaborate terminology by which the petrologic assemblages exposed in valley sides and cliff faces may be characterized. In explanation of these omissions it may be said that many pages might easily have been filled with such material, if I had so desired, by extracts from the writings of Agassiz, Mayor, Gardiner, Voeltzkow, Hedley, Vaughan, and other competent biologists and from those of Lacroix, Iddings, Marshall, Daly, Foye, and other experienced petrologists. But there are two reasons for excluding such evidences of what would be, on my part, mere pseudo-erudition. The chief reason is

that I have never acquired any real familiarity with biological or petrological terminology; the other is that the broad fields of investigation in which those terminologies have grown up so luxuriantly are outside the narrower field of physiographic geology which I have chosen to cultivate.

Had either biology or petrology been of essential importance in the phase of the coral reef problem here under discussion, I would have made an effort to "book up" enough to give those sciences at least a fair treatment; but as a matter of fact they have no such importance. Hence even the height of the respect that I feel for the scientific discoveries there made does not equal the depth of the ignorance in which I contentedly remain concerning their etymological inventions. As far as volcanic islands are concerned, a ragged spur-end cliff fronted by a ledgy rock platform of abrasion or a thick lava bed outcropping on the side slope of a well-opened and partly embayed valley is sufficiently described for my purposes in those untechnical terms. And whatever the assemblage of cannon-ball, all-thumbs, or other heavy corals in the surf of exposed reef fronts, or of branching-bush, fern-frond, or other delicate corals in the quiet waters of lagoons—for so I described various forms in my notebooks—the reefs to which they belong are sufficiently defined for my purposes in such phrases as narrow or broad fringes or as close-set or distant barriers.

The fact that the rocks of a certain island, as determined by a competent specialist, are medium grained, mafic gabbros passing into holocrystalline porphyry and trachydoloritic basalts, containing either occasional phenocrysts or more abundant anhedral tabular crystals of andesine, is undoubtedly as worthy a subject for scientific study as any other; but it does not aid in the least in determining whether the wall-and-bench notches in the spur ends around an island shore are cut, as they often appear to be, in sine-and-cosine relation in slanting cliff faces of earlier origin, the partial submergence of which is therefore inferred to have been rapid. Examples of such cliff-face notches have been mentioned in the account of the Marquesas and other islands.

Similarly, the fact that a close-set barrier near the base of a precipitous island scarp contained numerous genera of true corals, recognized by a widely traveled expert as including Millepora, Tubipora, Pocillopora, Prionastra, and many others, may well show that for variety and luxuriance of growth the reef is unusually prolific; but that biologically interesting fact does not help at all in recognizing that the island scarp is a slightly eroded, pikestaff fault face—I call it so because it is physiographically so plain to see—which plunges rapidly beneath the barrier reef on the western side of an uptilted block of bedded lavas, while on the eastern slope of the island the tilted block slants down with the dip of the lava beds in a moderately dissected surface to a somewhat embayed shore line and apparently descends a good thousand feet or more beneath the distant barrier reef on that side. The island thus summarized is Wakaya in the Fiji group. Attractive as petrologic and biologic problems are to their

devotees, it has been my experience that the physiographic aspects of coral reef investigation may alone give a student, somewhat advanced in years, quite as much work abroad and at home as he is able to accomplish.

In any case, whether an island has long remained stationary while reefs grew outward from it or whether it has intermittently subsided while reefs grew up around it is a matter that has no relation whatever to its petrologic constitution; and whether a continuous barrier reef has grown up from discontinuous fringing reefs during their deep submergence by slow subsidence or has grown up during the rise of the ocean over a relatively shallow rock platform cut in a stationary island by low-level abrasion is in like manner not to be determined by a study of the plants and animals in the present reef population, but by a study of the island that the reef encircles. It is for this reason that the present volume on coral reefs has, for its frontispiece, a view of one of the grandest peaks of all reef-encircled islands in the Pacific.

Reef growth truly depends in the smaller way on the intimate symbiotic relations of polyps, algae, and other reef-building organisms; but reef growth is conditioned in the larger way chiefly by other than biological factors, such as changes of ocean level and temperature, presence or absence of loose detritus on shores and of suspended detritus in the shore waters, and movements of elevation or subsidence in the reef foundation. The determination of these primary, non-biological factors involves a series of considerations altogether unlike those entering into biological and petrological problems.

The Place of Deduction in the Study of Coral Reefs

It may be hardly necessary here to say again what has been already stated as to the great importance of deduction in such a study as that of the origin of coral reefs. Induction is of course fundamental and essential as a means of securing a general knowledge of the facts whose origin is sought; but, inasmuch as the origin of the facts lies in the past, it cannot be reached by induction alone but only through a proper combination of induction and deduction. As deduction is thus seen to be a necessary, indeed an indispensable, process, it is desirable that it should be performed just as consciously and as carefully as induction. The importance of extending Darwin's theory by the deduction of its essential consequences has already been sufficiently shown. The disastrous consequences of the omission of deduction from certain alternative theories proposed about half a century ago has been pointed out in Chapters III and IV. The aid afforded by deduction in the definition and recognition of the marginal belts of the coral seas may be measured by returning to the chapter concerned with those belts.

But it still remains to emphasize the importance of carrying over from those earlier sections and chapters into the several chapters here opening

the deduced consequences by which various theories are characterized and of repeatedly confronting these consequences with the array of facts now to be set forth. Only then will the facts rise from their local value as mere items of occurrence in the coral seas to their broader value as tests of various rival hypotheses. Clearly, they can gain this broader value only if the consequences of the hypotheses are just as definitely conceived as the facts are observed. Indeed, if the consequences of the hypotheses are well worked out they will, as a rule, be conceived much more completely than the facts are observed; for, while the descriptions of observed facts are concerned only with their actual and visible surface features, the concepts of hypothetical consequences reach their internal structure and their past origin just as well as their surface; and therein lies one of their chief values. For, when the consequences derived from a certain hypothesis are confronted with the appropriate facts so successfully as to permit, nay, to compel the adoption of that hypothesis as the true theory by which the facts are to be explained, then the transparence of the consequences will enable the observer to treat the facts also as transparent and to state with much confidence—though properly always as a theoretical extension from observation to inference—the understructures upon which the surface facts are based. One of the best illustrations of this phase of the present study is that which suggests that the central islands of barrier reefs, which have no cliffs at the visible ends of their inter-bay spurs, in reality have cliffs submerged below sea level at the actual ends of their spurs, as will be recalled when those islands are described on a later page.

Reefless Coasts of Large Islands

Good support for the belief that fringing reefs cannot be formed on shores where firm rock is wanting is given by the reefless coasts of several large islands on which evidence indicative of recent emergence is found.

Java and Sumatra

Much of the southern coast of Java, HO 3004, 3005, has been rather heavily cloaked with downwashed volcanic detritus. It is now, according to Guppy (1889), bordered by "beaches of dark volcanic sand, on which the heavy rollers break without the intervention of coral reefs"; these beaches "form the prevailing feature of the coast." In certain stretches of this shore earlier-formed fringing reefs are described as having been overwhelmed by the sand and silt brought down by rivers and distributed by waves and currents. The mid-southwest coast of Sumatra, Ho 3100, 3101, repeats these features. According to Erb (1905), a coastal plain of Pliocene deposits, there lately uplifted, is traversed by young valleys from which abundant gravels and sands are outwashed and swept northwestward by the longshore currents on the beach of a simple shore line, seaward from which is a shelf 10 or 20 miles wide. Farther southeast, where

there is less littoral detritus, both sea-level and uplifted fringing reefs, the latter 70 or 100 feet above sea level, are found.

Valkenburg explains (1921) that a young anticline, increased in volume by volcanic deposits, forms the Barisan mountain range, parallel to the southwest Sumatran coast and 10 or 15 miles inland, and that the shore line, originally lying on the seaward flank of the anticline, has been gradually prograded by delta deposits and by wave-built sand beaches where no coral reefs are found. He adds that a 20-mile interruption of the beached shore line is occasioned by the rocky and embayed salient of a well dissected volcanic mass, which apparently stands far enough from the Barisan anticlinal axis to have taken part in a synclinal depression by which the deep Mentawei sea trough has been formed between Sumatra and a range of outlying islands; the headlands of this salient bear small fringing reefs.

Much of the coast of Borneo appears to be bordered by lowlands of emergence without reefs, as will be briefly stated again on a later page in connection with the shallow Sunda Sea, which that great island limits on the northeast.

Madagascar

Two other large islands, Madagascar and Taiwan or Formosa, may be described here in part, as their east coasts, apparently defined by recent upfaulting or flexing, are usually beached and reefless. The extraordinarily rectilinear east coast of Madagascar, already referred to under the marginal belt of the Indian Ocean, is explained by Lemoine (1911, p. 28) as due to downfaulting; but it seems more probable that a double movement, involving flexing as well as faulting, has taken place. The mountains that rise not far inland are formed largely of ancient crystalline rocks and are drained by rapid streams flowing down young valleys to a narrow alluvial shore belt where long sand beaches are charted, BA 759B, 758, for 700 miles. The beaches frequently enclose linear lagoons and are fronted by a narrow submarine shelf which falls off steeply to deep water. J. Allan, as quoted by Darwin (1842, p. 58), appears to have been wrong in reporting that along this coast "almost every headland and low point of sand has a coral reef extending from it in a S. W. and N. E. line, parallel to the currents." No such reefs are shown on the charts. A narrative of a boat trip along the lagoons by Rooke (1866), before the days of explanatory physiography, and an empirical account of the coast by Grandidier 20 years later (1886) give little consideration to the origin of the sand reefs. Burleigh, who later visited this coast (1896), naturally did not give special attention to the absence of coral reefs along it; but he presents a good though brief statement of the facts: "The mid-part of the east coast of Madagascar presents the aspect of long stretches of white or yellow sandy beach, capped by low sand hills . . . part of a natural embankment which varies in height from 20 to 70

feet, and in width from 20 yards to several hundreds. It seems to shut off the sea and enclose between itself and the real mainland, narrow freshwater lagoons" (1896, p. 33).

Even St. Mary's Island, 30 miles long by 2 or 3 wide, 400 feet high, rising near the outer border of the littoral shelf 250 miles from the northern end of Madagascar, has no charted reefs. Their absence from an island so well situated as this is probably due to recent and rapid movement coupled with Postglacial ocean rise; for reefs occur around other islands in about the same latitude farther east, where the same ocean rise has therefore presumably not been coupled with so rapid a movement.

The western coast of Madagascar, on which a short bank barrier probably belonging in the marginal belt in latitude 22° S has been earlier described, presents along much of its mid-length little indication of submergence in the way of drowned-valley embayments. It is bordered by a rather large shelf, which attains a breadth of 50 miles or more, but the shelf bears only scattered reef patches. About latitude 19° S, soundings indicate a narrow submerged reef on the shelf, apparently a bank reef, at depths of from 4 to 9 fathoms, 15 or 20 miles offshore, with depth of 13 to 17 fathoms back of it. The greatest development of reefs is in connection with the small Barren Islands, BA 2461, which rise from the shelf about latitude 18½° S; they are mostly less than a mile in length and vary in height from 30 to 100 feet; fringing reefs 1 or 2 miles wide surround them, and a few reef patches of similar size stand alone, as if covering submerged islands.

The northwest coast, BA 758, is somewhat embayed, especially at the northern end of the island; the shelf is from 10 to 30 miles wide along this stretch; and on its outer border is a discontinuous barrier reef, with small patches here and there awash but generally 5 or 10 fathoms under water, of which Lemoine makes brief mention (1906; 1911, p. 17). The incomplete development of reefs along the west coast and around the north coast of the great island is paralleled by the imperfect growth of reef rims on many banks in the neighboring part of the Indian Ocean and may be plausibly ascribed to recent and rapid subsidence, probably coupled with ocean rise as above noted. This inference accords well with the geological conclusions generally accepted as to the great subsidence of a continental area that has extended the basin of the Indian Ocean. The flourishing condition of barrier-reef growth around the embayed volcanic island of Mayotta, 180 miles to the northwest of Madagascar, is exceptional in that ocean, as will be further told in a later chapter.

Formosa

Formosa or Taiwan, HO 3176, 210 by 25 miles, with many mountains over 10,000 feet high east of its mid-line, has a bold eastern slope and an eastern shore line of simple pattern with a rapid descent to deep water. It has a more gradual descent to the west coast, where it is connected all

along its length with the minutely embayed coast of China, 100 miles distant, by a bank or continental shelf 30 or 40 fathoms in depth. The island has the appearance of an uplifted fault block; appropriately to such an origin it is without embayments, and few if any coral reefs are charted on its shores; but Yabe and Hanzawa report cliffs of raised reefs on its southwestern end (1923, p. 1135). Such reefs suggest pauses in uplift; but, if they lie unconformably on the island rocks, a triple movement would be indicated.

It may be further inferred for Madagascar as well as for Taiwan, that the downfaulted or downflexed eastern half of the original mass was depressed so rapidly that reef upgrowth could not keep pace with it; hence no atolls survive to memorialize its disappearance.

The Pescadores group, HO 2558, consists of tabular islands, 100 feet or more in height, rising from the shallow sea near Formosa on the southwest. The shores are well embayed, and the sloping, non-cliffed spurs are here and there bordered with fringing reefs up to a mile in width. This suggests that the tilting of the uplifted fault block of Formosa caused the depression of these islands; the depression was probably rapid, as the present reefs are fringes instead of barriers. A number of smaller islands farther south in the same shallow sea have no reefs, as will be told below.

Non-embayed, Reefless, Continental Coasts of the Indian Ocean

Long stretches of the continental coasts on the west and north sides of the Indian Ocean are for the most part reefless, presumably because of the prevalence of muddy water over the shallow shelves of unconsolidated sediments which adjoin them. The torrid eastern coast of Africa, HO 1602–1606, has as a rule a simple, beach-bordered outline and is fronted by a continental shelf 10 or 20 miles wide with no outlying islands except Zanzibar and its neighbors, which will be mentioned in the chapter on elevated reefs. The mainland coast is without reefs for long distances, except that discontinuous shore reefs occur between latitude 12° S and the equator; they are reefs that Darwin actually classed with fringing reefs because the lagoons enclosed by them are very shallow. A passing view that I had of these reefs near Mombasa in 1905, on a return voyage from South Africa, suggested that their growth may have been associated with a slight and recent submergence and hence with the Postglacial rise of ocean level: the chief recent movement of the East African coast seems to be one of emergence.

Similar conditions prevail along part of the southeast coast of Arabia, HO 1586, 1587. Where the coast of that desert region retreats in the Bay of Khorya Morya, it is fronted by a shelf or bank from 30 to 50 fathoms deep; but next to the southwest is a shelfless salient of exceptional

character in that it has a ragged, apparently embayed outline and yet is without reefs. From the Gulf of Oman to Karachi, HO 1588, and along the west coast of India as far as Bombay, HO 1589, there is a generally reefless shelf from 50 to 80 or 100 miles wide and about 50 fathoms deep at its outer border; a few fringing reefs follow the shore. South of Bombay, HO 1590, where the shelf narrows to 50 or 30 miles, the coast is still beached and reefless, although it has a few embayments. The down-

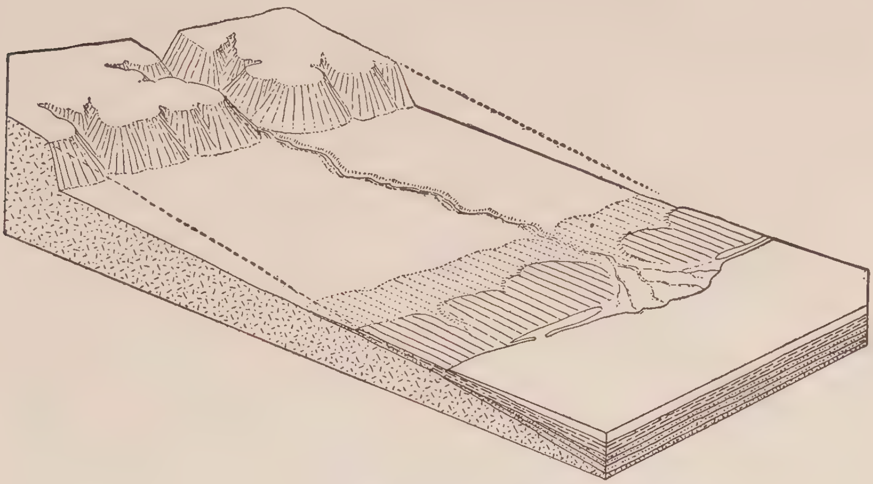


Fig. 99—Block diagram of the reefless Madras coast.

faulting and deep submergence of a former western extension of southwestern India will be considered in the account of the Maldive atolls, in Chapter XVIII. Around the southern extremity of India and thence northeastward to Ceylon, HO 1591, the continental shelf is well developed, its border being 50 or more fathoms in depth; no islands rise from it. The shore is generally reefless, except that Ceylon has discontinuous fringing reefs and that two submerged barrier reefs rise 15 or 20 miles off its southeastern side. Adams Bridge, a wave-and-current-built shoal, by which Ceylon is connected with the mainland, has been studied by Walther (1891).

An excellent example of a reefless continental coast of emergence is found in the Madras district of southeastern India, HO 2433, 2434, which has been well described by Cushing (1911; 1913). The unconsolidated deposits of a former sea floor have here (Fig. 99) been partly laid bare. Mature sea cliffs, from which the deposits were largely derived during a former period of lower stand and long continued abrasion, now rise several miles inland. In the absence of protecting coral reefs a long cordon of offshore sand reefs, alternating here and there with deltas, has been built up by the surf. Mention will be made later of the striking and instructive contrast of this reefless coast of emergence with that of the

northeastern side of New Caledonia, where it is believed that the similarly mature cliffs of a former abrasion period are now partly submerged and where a barrier reef several miles offshore now encloses a lagoon in front of them.

The northern shore of the Bay of Bengal, HO 1593, is largely occupied with deltas which have been built out by great rivers in spite of possible subsidence and of strong wave attack; the deltas are extended seaward in a broad shelf. This low stretch is wholly reefless and is in this respect like the mid-southern coast of New Guinea, HO 2944, 2945, where the delta of the Fly River forms extensive flats and shoals, described long ago by Jukes (1847).

The absence of reefs along the greater part of the Indian Ocean coasts here reviewed is manifestly due to the unsuitable conditions offered for coral growth by the shifting sediments of shore beaches and of continental shelves, most of which appear to have been formed previous to or in association with recent continental emergence, as will be recalled when the Great Barrier Reef of northeastern Australia is described.

Embayed and Reefless Coasts of Southeastern Asia

The coast of southeastern Asia, from the head of the Bay of Bengal around the Malay Peninsula to the middle coast of China, is like the continental coast of the Indian Ocean, above described, in being prevailingly reefless and in being fronted by a shallow submarine shelf; but it is very unlike it in being strongly embayed and in having a large number of outlying islands. This is strikingly the case on the eastern side of the Bay of Bengal in the Gulf of Martaban, BA 70, where a swarm of reefless islands rise from shallow water; and again in the Mergui archipelago, BA 216a, where the shelf is from 5 to 50 miles wide and where some of the reefless islands are 30 miles from the mainland; and still again farther southeast, BA 842, where a number of well embayed islands rise on the shelf from 10 to 30 miles off the mainland.

Similar conditions appear to have long prevailed on the east coast of the Malay Peninsula, HO 3131, 3132, 3133, which faces the great expanse of shallow water known as the Sunda Sea, where depths of only 5 or 10 fathoms are sometimes found 10 or 20 miles offshore. Here the outlying Ridang, Anamba (Fig. 25), and other islands have well embayed shores like the mainland and like the mainland are reefless, except for short fringes. Farther north, the outcurving mountainous coast of Indo-China or Annam, HO 3148, 3152, faces the deepest central area of the China Sea; here only a narrow shelf separates the land and sea areas. This Annam coast was formerly better embayed than now: as described by Chassigneux (1918) it has been simplified by the construction of many beaches between the reefless and slightly abraded headlands, the bays enclosed behind the beaches being largely filled with delta plains. For some

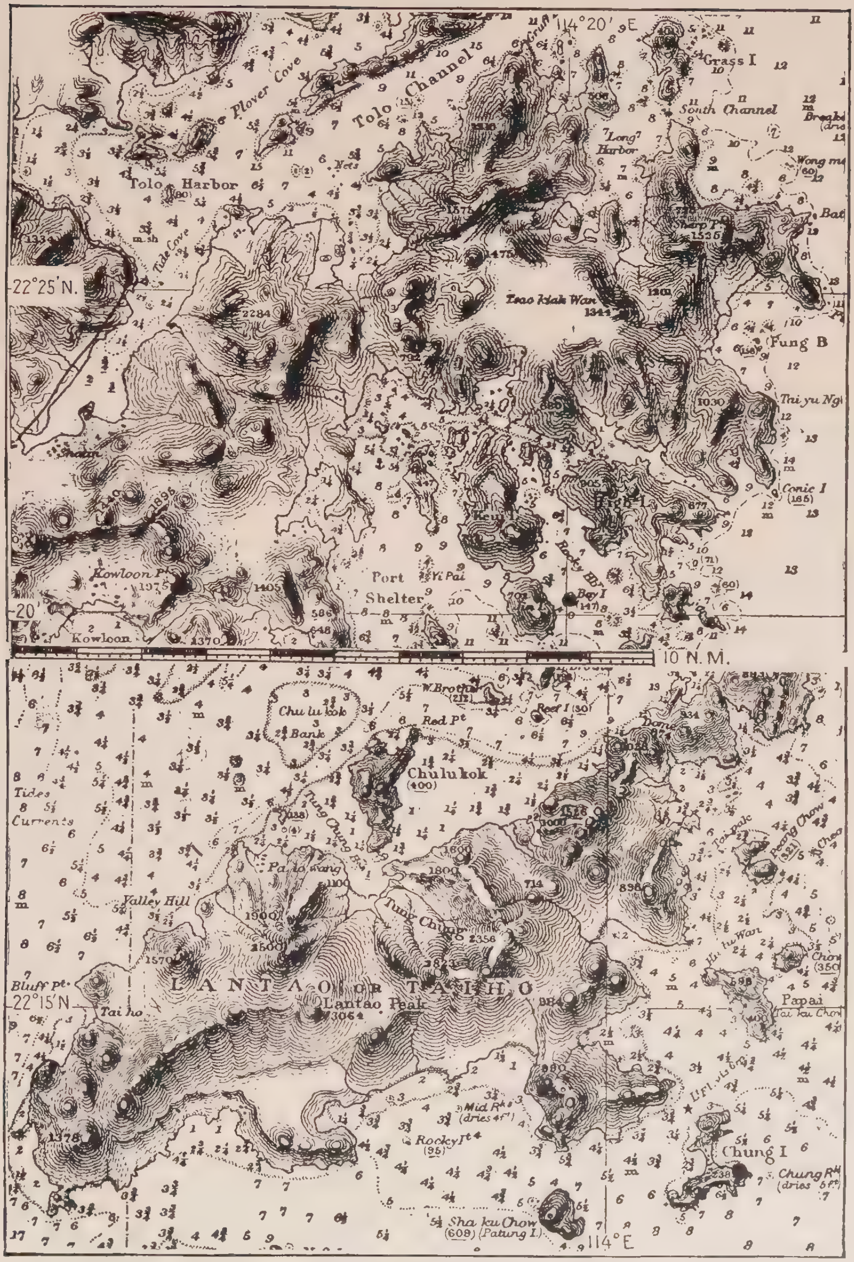


FIG. 100—Embayed and reefless islands near Hongkong, China; HO 3199.

400 miles along the coast of China a broad shelf again extends seaward, from the neighborhood of Hongkong to the limits of the coral sea about latitude 24° or 25° N, HO 3170, 3174, 3176, 3178. The outlying islands here (Fig. 100) are as free from reefs as those on the east side of the Bay of Bengal.

Farther north the islands of the Pescadores group, HO 2558, 100 feet or more in height, rise from the shallow sea southwest of Formosa, in the account of which they have been briefly mentioned. They are like the islands farther south in having well embayed shores but unlike them in being bordered here and there by fringing reefs up to a mile in width. No satisfactory reason is found for this difference, unless it may be that the southern islands have been more recently submerged; but the presence of reefs here shows that their absence farther south cannot be due to a deficiency of warmth in the sea water.

The erosion of the now submerged valleys of the mainland and the islands, as well as of the much broader valley lowlands between the mainland and the islands, on this long stretch of coast around southeastern Asia surely demands a greater emergence and a vastly longer time than can be provided during the Glacial epochs of lowered sea level. It may therefore be suggested that after a long time of greater emergence and deep erosion, gradual submergence permitted large rivers, fed in lofty mountains, to cause the outward growth of extensive delta plains, by which many outlying islands were enwrapped at progressively higher and higher levels and contemporary reef growth was prevented, and that when those aggraded plains were drowned by the greater submergence of today the turbidity of the shore waters prevented the beginning of fringing reefs and their upgrowth as barrier reefs. During the Glacial epochs erosion must have been renewed in the distal parts of the valleys as far as they were laid bare; but the work then accomplished must have been short-lived and small compared with what had been done before.

The Reefless Sunda Sea and Its Embayed Islands

A large area of shallow water, varying hardly more than from 20 to 40 fathoms in depth, includes the South China and Java Seas and has been given the single name, Sunda Sea. Its low coasts are reefless because, as Sluiter has well explained (1890), of the muddiness of the shores and because of the turbidity and brackishness of the sea water near the mouths of large rivers. Corals may locally begin to grow on water-logged fragments of pumice stone, but they seldom have opportunity of extended growth; hence only a few small reef patches are found north of Java. Farther northwest, especially in the neighborhood of the Malay Peninsula, Sumatra, and western Borneo, HO 797, the sea is interrupted by many islands—Molengraaff has counted 3966 of them on large-scale Dutch charts—with minutely irregular shore lines, on which fringing reefs are

discontinuously developed but around which barrier reefs are unknown. The Riou and the Lingga archipelagoes, HO 1205, 3747, structural extensions of the Malay Peninsula, are typical examples. As described by Molengraaff (1922, pp. 283, 317) they consist in part of steep-dipping strata, including quartzites, greatly eroded since their formation and deformation. To the east and north are the Tambelan, Anamba (Fig. 25), and Natuna groups, HO 3096, 3038, 3039, 3036, all well embayed but imperfectly reefed.

The advanced dissection of resistant rocks in these island groups seems to call for a longer time of erosion than the Glacial epochs could afford and hence to imply that some of their dissection was accomplished with respect to normal ocean level when the region stood higher than now. In this case a gentle and recent downwarping of the region would be chiefly responsible for the present submergence. In any event, the absence of barrier reefs around the islands of the Sunda Sea appears to be sufficiently explained by the unfavorable conditions offered for their origin as fringing reefs along the shallow and muddy shores before the recent downwarping occurred.

The Embayed Northwestern Coast of Australia

The features described in the preceding section for the shallow Sunda Sea are repeated in the equally shallow Arafura Sea, which lies on a continental shelf, known as the Sahul Bank, along the northern and northwestern coast of Australia. The shore line here, HO 3418, 3419, 3420, 3421, is greatly embayed along a stretch of 800 miles; many embayed islands, generally without fringing reefs, rise from the shelf, which has a width of about 60 miles and a marginal depth of about 40 fathoms. The shelf is, however, unlike the shallow floor of the Sunda Sea in bearing a number of more or less perfect bank atolls, the largest of which are not far from the mainland.

These atolls are: Long reef, 15 by 5 miles, with unreefed shoals extending 10 miles to the north; East Holothuria, which with its shoal measures 28 by 15 miles; Adèle, 15 by 6 miles; Lacepède, 8 by 3 miles, with reef patches for 15 miles northwest. Five normal atolls stand outside of the shelf margin in relatively deep water: Scott, 20 by 15 miles; Seringapatam, 7 by 4 miles; and, farther southwest, Mermaid, 9 by 6 miles; Clarke, 10 by 6 miles; Impérieuse, 10 by 5 miles. Opportunity for reef growth has therefore been much better here, for some unknown reason, than in the Sunda Sea; yet the shelf margin is not marked by even an imperfect barrier reef such as will later be described as lying along the eastern margin of the shallow Sunda Sea floor southeast of Borneo. The Aru Islands, HO 3027, which rise with irregular shore lines near the margin of the northern extension of the Sahul bank where it approaches western New Guinea, have only occasional fringing reefs on short stretches of their

shores; they may therefore be compared with the Riou and Lingga Islands above named, near Singapore, except that the Aru Islands are composed of limestone: they are again mentioned in Chapter XVI.

The great Sahul shelf undoubtedly demands for its production a long period of erosion on the rainy northern coast of Australia, when much detritus was washed out for deposition on the neighboring sea floor. The shelf probably began to grow on a downwarped marginal belt of the formerly more extensive mainland, the disappearance of which is clearly indicated by the elaborate embayments of the present mainland shore. It is easily conceivable that a barrier reef, like that now fronting the Queensland coast, may have grown up for a time from the outer border of the downwarped area at an early stage of its disappearance; but if so the reef has been subsequently drowned by rapid depression or buried by deposition. No traces of it now exist. The existing atolls, both on and outside of the shelf are probably based on submerged rocky islands; but why the first establishment of the shelf atolls as fringing reefs was not prevented here, as it seems to have been elsewhere, by turbidity of the sea water is not understood.

Northwestern New Guinea

The northwestern part of New Guinea, HO 2980, 2981, resembles the continental coasts just described in having an embayed shore line, in being fronted by an extensive continental shelf, and in having no offshore barrier reefs. Much of the continental coast of the Caribbean Sea, which represents the restricted coral sea of the Atlantic, is also prevailingly reef-free, apparently for the same reasons as those which exclude reefs from the other continental coasts already described. The muddy and reef-free coast of northeastern South America has been mentioned under the marginal belt of the Atlantic.

Summary for Reefless Continental Coasts

It is clear from the foregoing rapid survey of the continental coasts of the coral seas that they do not as a rule offer favorable conditions for coral growth. As to the reasons for these unfavorable conditions, the coasts fall into two classes. First are the simple coasts of recent emergence, such as for the most part those of the Indian Ocean west of the Bay of Bengal appear to be; they are bordered by unconsolidated sediments on which reef-building corals can seldom establish themselves. Corals have truly enough in some way succeeded in forming offshore bank barriers along part of the eastern coast of torrid Africa; but that stretch of coast is peculiar in this respect.

Second are the embayed continental coasts of submergence such as those of southeastern Asia, east of the Bay of Bengal. Here it might be expected that barrier reefs, or at least fringing reefs of a new generation,

would be abundantly developed today; but as a matter of fact barrier reefs are altogether wanting along those coasts, and even fringing reefs are imperfectly developed if at all. The occurrence of the greatest barrier reef of the world along the submerged continental coast of northeastern Australia will later be shown to be altogether exceptional.

The most reasonable explanation for the absence of reefs along these mountainous, embayed coasts is that, as above suggested, the coasts have formerly stood at a much greater altitude than now, exposed to long-continued subaerial erosion while drained by large rivers, so that they have shed enormous volumes of detritus into the adjacent seas. The formation of the present continental shelf was thus well advanced. But during the long continuance of erosion, the coasts have been lowered, detaching many islands from the mainland, and thus initiating on mainland and islands alike the shore-line embayments by which they are now so strikingly characterized, while the continental shelf was more and more aggraded. At times of slower submergence, recently favored by the lowering of ocean level as a Glacial epoch came on, the outlying islands may have been united to the mainland by forward-growing delta plains; while at times of more rapid submergence, favored by a rising ocean level on the return of a genial climate, the land-tied islands have been isolated again. It is evidently in virtue of the extensive highland areas of heavy, torrid rainfall that the outwash of detritus from these coasts has been large enough to maintain a shallow shelf along them in spite of their subsidence. And it would appear to be because of the maintenance of the shelf that coral reefs have not had opportunity of development, in spite of the suitable temperature of the sea water and of the favoring subsidence of the coast.

CHAPTER X

REEFLESS YOUNG VOLCANIC ISLANDS IN THE CORAL SEAS

Outline of Inquiry

It is desired here to determine whether the shores of young volcanic islands become the seat of persistent fringing reefs as soon as their eruptive growth ceases or whether they continue for the most part reefless as long as they remain stationary, thus postponing the establishment of well defined reefs until submergence, due either to ocean rise or island sinking, embays their valleys. It is also desired to discover whether any young volcanic islands in the coral seas have remained stationary and reefless long enough to be greatly cliffed or whether, if no or few greatly cliffed islands are found, it may be inferred that volcanic islands do not as a rule long remain stationary. It should be recalled that in the account of the North Pacific marginal belt, a section was devoted to setting aside the old belief that active volcanoes are associated with crustal upheaval and to showing that their eruptive growth may have accompanied their subsidence on a sinking sea floor.

Young Volcanic Islands in the Australasian Seas

Wallace long ago noted in his brief account of the cones of Ternate, Tidore, and Makian, in contrast with other islands west of Halmahera (Gilolo) in the Dutch East Indies, that "the coasts of these small islands are very different according to their geological formation. The volcanoes, active or extinct, have steep black beaches of volcanic sand, or are fringed with rugged masses of lava and basalt. Coral is generally absent, occurring only in small patches in quiet bays, and rarely or never forming reefs . . . Islands of volcanic origin, not themselves volcanoes [that is, not now active?], but which have been probably recently upraised, are generally more or less completely surrounded by fringing reefs of coral, and have beaches of shining white coral sand" (1869, p. 327). Why the reef-fringed islands were supposed to have been upraised is not stated; perhaps the supposition was merely an application of Darwin's generalization that fringing reefs characterize rising coasts.

Gunong Api, the highest member of the Banda group, HO 3022, south of Ceram in the Dutch East Indies, is a young cone around the shore of which, according to the *Challenger* Narrative, corals are seen in "huge masses . . . which have their bases attached to the bare basaltic rock of the shore. The tops of all these coral masses are dead and flat and some-

what decayed; but on these dead tops fresh growth is taking place, showing that slight oscillations in the level of these shores of a foot at least have recently taken place" (1885, Part II, p. 565). Verbeek has published in his account of the Banda islands (1900) a superb half-tone panorama and a contoured map, 1:20,000, of this cone. The cone is thus shown to be so young that its slopes are hardly furrowed by ravines and its shores are not perceptibly cut back in low bluffs. Hence it is quite possible that the present fringing reef, which is a trifling affair in spite of its including "huge masses" of coral, may be smothered as the future erosion of ravines advances down the slopes of the cone and a greater volume of detritus is delivered to the shore; abrasion will then be wholly unhindered.

Weber's report upon the Siboga expedition gives a view of Gunong Ija, an ash cone off the south coast of Flores (1902, p. 147), on which no fringing reefs seem to have been formed; the discharge of detritus from this steep cone must be very rapid. Molengraaff (1916a) describes the young volcanoes which form the island of Dammer, 9 by 7 miles, not far from the Banda islands; a fringe of coral lies near the western coast at a height of 25 or 30 feet. The circular volcanic island, Sangeang, next northeast of Sumbawa, HO 3006, 7 miles in diameter, 6335 feet high, is little modified from its initial form; it is therefore very unlike the dissected and well embayed island of Banta, 4 miles in diameter, 1314 feet high, 14 miles to the southeast. Several young cones north of Celebes have been described by Hickson, who visited the region for zoölogical study (1889). Of these Ruang, about 2200 feet high, is of simple conical form with a smoking crater; the shore is a little cliffed in part of its circuit and generally has a beach of fine black sand with waterworn coral fragments but no reefs. This active volcano was unwarrantably taken by Hickson to disprove the occurrence of subsidence in connection with the formation of some near-by atolls. In the Philippines, the enclosed Samar Sea, CS 4418, shows Maripipi Island as a circular cone, 3½ miles in diameter and 3000 feet high, apparently a young volcano, without cliffs or reefs. Ferguson has described several small islands north of Luzon as composed in part of volcanic rocks, in part of limestone; they are more or less cliffed and reef-fringed (1908). The weakness of reefs here is perhaps because the islands have suffered various changes of level, the latest of which appear to be so recent that reef growth is as yet little developed around their shores.

The sea northeast of middle New Guinea contains a number of young volcanic islands, but accounts of them by Finsch (1888, p. 365) and von Pfeil (1899, p. 181) are meager. On the west and north of the Gazelle Peninsula, New Britain, HO chart 2970 represents two conical islands, presumably young volcanoes: Lolobau, 5 miles in diameter, 3058 feet high; and Watom, 2 miles in diameter, 1115 feet high; both have simple shore lines without reefs.

Volcanic Islands in the Solomon, Santa Cruz, Banks, and New Hebrides Groups

At the northwest end of New Georgia, the large, south-central island of the Solomon group, is a superb example of a volcanic cone, Kulambangra, HO 2902, 15 miles in diameter, 5450 feet high, little dissected, and having a minutely irregular shore line, apparently due in part to inequalities of incipient abrasion, as along the northeast shore, and in part to the slight submergence of young valleys, as on the southeast. Narrow fringing reefs stand a little offshore on the western side and thus suggest an early stage of barrier-reef development. At the other end of New Georgia is the cone of Vangunu, HO 2907, about 12 miles in diameter and 3686 feet high, apparently of composite origin. It is elaborately dissected and well embayed as if by rather strong submergence on the older northern side (Fig. 195), yet it is little changed from a simple initial form and but moderately submerged on the younger southern side. Clearly this suggests that the subsidence of the older mass continued while the younger mass was in process of eruptive growth. A reef which presumably began as an onshore fringe on the southern side of the island is now an offshore and partly submerged barrier; the southward detour made by this reef probably loops around a completely submerged dependence of the main island. It is noteworthy that a small, drowned atoll near by has the unusual lagoon depth of 51 fathoms, a few fathoms of which may be credited to the recent subsidence by which the atoll reef was drowned. Further complications in the history of this remarkable island are told in Chapter XV. Between the large islands of Guadalcanar and Florida is the small cone of Savo, HO 2916, 4 miles in diameter, 1673 feet high, little dissected, moderately cliffed, and reefless.

The small Santa Cruz group, east of the Solomons and north of the New Hebrides, HO 1985, contains one reefless young volcanic cone, Tinakula, a mile in diameter, 2200 feet high. The islands of the Banks group, between the Santa Cruz and New Hebrides, HO 2877, are mostly of recent formation. According to Mawson they "are almost wholly volcanic in origin, reef débris taking only a very small share in their formation; as a result they are high and rugged" (1905, p. 424); but Reef Island is of crescentic outline with a fringing reef flat 1 or 2 miles wide. Tucopia, a lone island 100 miles northeast of the Banks group, of subtriangular outline 2 miles on a side, rises 1235 feet to a breached crater; it has narrow fringing reefs.

The New Hebrides group includes a number of volcanic cones, some of which are active. One of them is Ambrym, HO 2890, 23 by 20 miles, 4380 feet high, on which I landed at two points in 1914. It is largely cloaked with ash deposits, on which the waves cut low bluffs and form reefless, black-sand beaches, where the surf gains a strange, inky turbidity as it falls. The plunging cliff of a small lava-flow salient, by which a

long, reefless beach is locally interrupted, bore individual corals on its firm rock face, apparently representing the embryonic stage of a fringing reef. North of the large island of Epi is the cone of Pauuma, 5 by 2 miles, 1825 feet high, with a simple shore, cliffed on the east, fringed with reefs on the west. North of Pauuma is Lopevi, 3½ miles in diameter, 4755 feet high; an active cone, with a simple, moderately cliffed, reefless shore.

Young Volcanoes in Fiji

Mbuke Levu on Kandavu

The Fiji group possesses few young volcanoes, as far as can be learned at present. One of the most conspicuous is Mbuke Levu or the Great

Fig. 101—Mbuke Levu, a young volcano at the western end of Kandavu, Fiji; looking west.

Yam-hill,* also known as Mt. Washington (Fig. 101); it is near the western end of Kandavu, the southwesternmost island of the group. Its cone is broadly truncated by a crater rim at a height of 2750 feet; on the northern side, facing the sea, the cone is strongly cliffed and reefless. Its first ascent is claimed by Seemann, after two unsuccessful attempts, in 1860; he described it as "evidently an extinct volcano . . . nearly 4000 feet high. . . . The outward look of the summit is very like the cone of Vesuvius, as it was . . . in 1861; but we did not discover any large crater, simply an insignificant swamp." The summit view included "a great part of Kandavu and the sea" (1862, pp. 215, 216). Kleinschmidt ascended the cone in 1876 and found it to give him the best outlook he had enjoyed in Fiji (1879, p. 262).

The Volcanoes of Taveuni

The lofty island of Taveuni in northeastern Fiji—called "Vuna" by Wilkes and persistently misprinted "Tavinni" in some narratives—HO 2851 (Fig. 102), is 23 miles long northeast-southwest and from 5 to 8 miles wide; it has a single crest which rises through its mid-length in four summits, 3590, 4040, 3920, and 3210 feet in height, all being little-modified volcanic cones. This island therefore rivals the much larger island of Viti Levu and exceeds its large neighbor Vanua Levu in height. One of the volcanoes was ascended by the botanist Seemann, who followed up a torrent bed of cascades and pools, in 1860; its top was "to all appearance

*In my account of "The Islands and Coral Reefs of Fiji" (1920a), the translation of this name was unfortunately given as the Great Yam, instead of the Great Yam-hill.

a large extinct crater filled with water" (1862, pp. 28, 29). Horne records: "There are no large streams on the island. In many instances the

FIG. 102—Taveuni and neighboring islands, Fiji; HO 2851.

water flows underground through caverns, which are numerous, and boils up on the beach, or a short distance out in the sea" (1881, p. 160). This seems to mean that erosion has not yet significantly modified the lava-flow caverns produced by eruption.

Andrews states that the island "contains numerous craters, one being nearly 3000 feet above sea level, with its rim fully 4000 feet above the sea; and streams of lava occur on a large scale." It was here that the "Earl and the Doctor," after their wreck on an atoll farther east, arrived in a boat and saw "the beautiful Tavinni [sic], the garden of the Fijis" (1872, p. 262). I had a good sight of the northwest coast of the island from a trading steamer in 1914 and made brief landings at two points, first near the southwest end of the island where several young cones and fresh lava beds (Fig. 103) were manifest, and later near the coast mid-length. The long, densely forested volcanic slopes of the high cones in the southwestern half of the island, roughly sketched in Figure 104, are steep, moderately

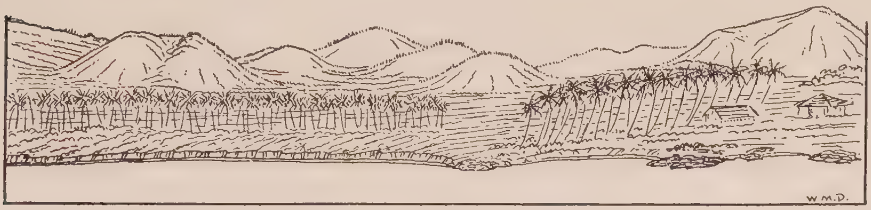


FIG. 103—Small volcanic cones, southwest end of Taveuni, Fiji; looking southeast.

concave, and little dissected; they receive abundant rain aloft and descend to a relatively simple and generally reefless shore line, which advances moderately in low lava salients or is cut back in low and rugged bluffs along slight reëntrants. The northeastern half of the island is more deeply dissected and has a more irregular shore line. This is probably because, according to Andrews (1900, p. 24) and Foye (1918, p. 37), the northeastern half is older and less covered with recent lavas than the southwestern.

In any case the southwestern half of Taveuni is exceptional among Fijian islands in its scanty coral growth. Reefs here appear at the sea surface only as narrow discontinuous fringes, with a rapid descent to depths of over 100 fathoms. On the other hand, around the older northeastern half of the island the charts show abundant fringing reefs up to a half a mile or more in width, outside of which lies a submarine bank two or three miles wide and 40 to 50 fathoms deep, bordered by an imperfect barrier reef at its northeastern extremity and continued eastward in a similar but somewhat shallower bank rimmed by a good barrier reef around the neighboring well embayed islands of Ngamia and Lauthala.

Gardiner proposed to explain the absence of reefs around southwestern Taveuni by the action of strong tidal currents in the strait that separates the middle of the island by only four miles from the adjacent Navukana promontory of Vanua Levu on the northwest (1898, p. 446); but, inasmuch as corals thrive in surf, it can hardly be that a tidal current of only five knots an hour can hinder their growth. Further, if tidal currents prevent reef growth on Taveuni, there should be no reefs on the well em-

bayed promontory across the strait; yet reefs abound there. Finally, the prohibitive effect of currents ought not to be felt on the southeastern side of Taveuni where the island faces the open Koro Sea; nevertheless, reefs are absent there. That that coast is cliffed like the northwestern coast is suggested by the legend "numerous cascades" on a large-scale chart. Agassiz noted that Taveuni is for the most part "destitute of reefs" (1899, p. 42), but he suggested no reason for its destitution.

The absence of reefs on the southwestern half of Taveuni is largely explained by the recency of its lava flows, under which earlier reefs have

Fig. 104—Low bluffs cut on the young volcanic slope of Taveuni, Fiji; looking east.

probably been buried and on which new reefs are as yet little developed. In evidence of the former existence of reefs, mention may be made of the well-formed Vuna reef, which extends as a V-like loop two miles out from the young lava flows that form the low southwestern end of the island. This loop seems to be the surviving extremity of a barrier reef which was elsewhere buried by the recent lava floods. Forbes, who spent two years, 1870-1871, in Fiji, sailed past the reef and described it as a gigantic breakwater, which "stretched boldly out to sea and defied the elements."

A second reason for the absence of reefs around Taveuni is, as already implied, pretty surely the abundance of detritus on the cliff-base beaches and offshore from them; the detritus is clearly destined to be more abundant still when the valleys are more deeply incised. Both cliffs and beaches should be better developed on the southeastern or windward side of the island, but it has not been possible to find any detailed account of that coast.

It may be noted in passing that the young volcanoes of Kandavu and Taveuni occur on islands and in regions that give independent evidence of having lately subsided. Thus confirmation is found here for the generalization presented in the account of Oahu in Chapter VIII, to the effect that there is no necessary association of volcanic eruptions and areas of upheaval.

The Island of Savaii, Samoa

Savaii, HO 2921, 40 by 22 miles, 6094 feet high, the westernmost, youngest, largest, and least embayed on the Samoan Islands, has been

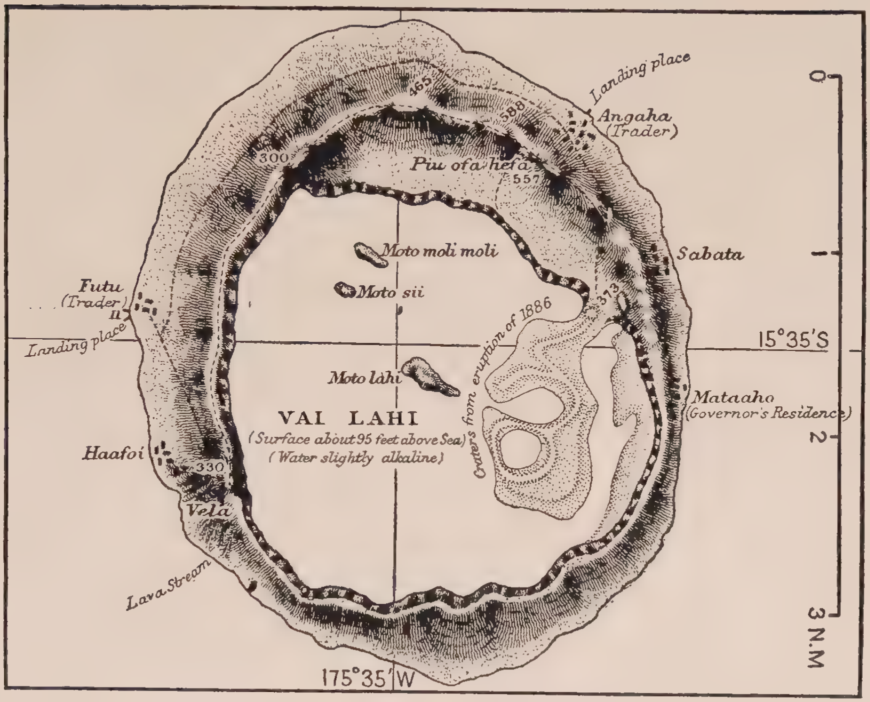


FIG. 105—The caldera ring of Niuafou; HO 1986.

frequently visited, especially in recent years, on account of its active central volcano from which lava streams flowed down the northern slope into the sea in 1906, 1907, and 1908. From early and later accounts by Wilkes (1845), Dana (1849), Krämer (1900, 1902–03, 1906), Wegener (1903), Sapper (1905-06), Angenheister (1909), Anderson (1910), and Friedländer (1910), one may gather various items, as follows: The slopes of the island are gentle, usually from 5° to 8°; over 60 parasitic cones have been counted; streams and valleys are imperfectly developed, but springs of fresh water gush out abundantly near or at the shore. In the absence of well-formed valleys the discharge of detritus is probably small as yet; patches of fringing reef, occupying in all an eighth or a tenth of the island circuit, seem to occur where the shore is somewhat cut back in low cliffs between salients formed by later flows. Whether submergence has taken place does not seem to have been especially inquired into; but Krämer (1900) makes it clear, after a tour around the island, that it bears no elevated coral rock, although such had been reported by earlier observers.

YOUNG VOLCANIC ISLANDS IN THE CENTRAL PACIFIC

Niuafou, HO 1986 (Fig. 105), is a ring island between Fiji and Samoa, 3 miles in diameter, with a crest from 350 to 588 feet in height. As described by Somerville (1896) it encloses a sheet of fresh water—a "lake

in the ocean"—2 miles in diameter and 95 feet above sea level, in which a a younger eruption has built a little peninsula. "The whole coast line is bounded by the most forbidding black lava rocks, on which the white surf continually breaks." The reefless shore is apparently so young that no beach lies on it.

It has often been remarked that a crater of this nature would, if it stood at a proper depth below sea level, form an admirable basis for an atoll; but it has been less generally understood that the most likely means of bringing such a crater to that depth is by subsidence after it had been built up by eruption to a moderate height above sea level. For, clearly, eruption alone cannot be expected to give a crater ring any particular relation to sea level; and, although upheaval might bring a submarine crater ring to the desired moderate depth, there is no reason to think that such a movement would stop at that depth. On the other hand, subsidence would lower a supermarine ring to the desired depth just as well as upheaval would raise it there, and while subsidence was in progress reef upgrowth from the outer slope of the ring might take place also. But upheaval, if continued, would cause a short-lived atoll on a crater ring to be succeeded after its emergence by a series of emerged fringing reefs on the crater-ring flanks, the like of which is unknown in the Pacific coral seas where atolls most abound. On the other hand, the subsidence would, if continued not too rapidly, result in the continuation of reef upgrowth, whereby a ring-crowning atoll would long continue to be an atoll; but a cone-crowning reef would make just as good an atoll, even if the cone had no crater in its summit.

Several young volcanic cones stand in line not far west of and parallel to the islands and banks of the Tonga group, HO 2016. Laté, 3 miles in diameter, 1700 feet high, is a crater-topped cone with low shore cliffs and no reefs. Tofua, farther south (Fig. 217), like Niuafou, is a caldera ring, 5 miles in diameter, 1600 feet high, holding a central lake 2 miles across and 140 feet above sea level; the shore is of simple outline and without reefs. Falcon Island, HO 2010, was produced by an explosive eruption about 40 years ago and has been described by Lister (1890), Wharton (1890), and Phillips (1899). It is now mostly washed away and reduced to a shoal. If reefs are eventually formed on the shallow foundation there provided they would, as Darwin recognized, constitute an atoll; but that most atolls are not of such origin is indicated by the mountain-top islands of almost-atolls.

Mehetia, the easternmost of the Society group, has been described by Agassiz as "an isolated volcanic peak nearly 1600 feet in height. . . . On the summit of the island a well marked crater exists. . . . On the eastern and southern faces the slopes of the island have been abruptly cut off, and terminate in vertical cliffs. . . . A few corals have been thrown up on the small beaches . . . along the east face and near the northeast point. On the western face considerable coral sand has been

thrown up . . . from the few coral patches . . . on the flat . . . of the western point" (1903a, p. 140). Further reference to this island will be made in the account of the Society group in Chapter XIII, where it will be shown to be the youngest of eight volcanic islands.

Young Volcanoes in the Mariana or Ladrone Group

This group of volcanic islands, HO 5360 and, on larger scale, HO 5358, 5359, is peculiar in having its 16 members arranged in two slightly offset lines with nearly meridional trends, between latitudes 21° and 13° N. It is adjoined on the southeast by one of the deepest troughs of the Pacific. Many of its islands are of distinctly conical form. The 11 northern members are reefless; the 5 southern members are partly or wholly covered with uplifted reef limestones. General descriptions of the islands have been written by Fritz (1902), Costenoble (1905), Prowazek (1913) and Hobbs (1923a). A few statements concerning the reef-bearing islands will be cited in a later chapter.

Young Volcanic Islands in the Indian Ocean

According to Hobday and Mallet (1885), Barren Island, east of the Andamans in the southeastern part of the Bay of Bengal, BA 825, consists of a caldera ring, 2 miles in diameter and 1000 feet high, enclosing a younger cone. The outer slope of the ring is "covered with dense tree jungle from near the sea level to the summit. . . . Of bare rock there is almost none, save where the lava has been eaten backwards into cliffs along the surf-washed coast." Narcondam, not far to the north, BA 825, is according to the same authors about 2 miles in diameter and 2300 feet in height; its slopes are deeply scored with ravines. "Except along the coast line, where . . . the rocks have been eaten back into cliffs, which sometimes tower above the sea to a height of several hundred feet, the island is covered with dense jungle." Neither of these islands is reef-fringed.

Four volcanic islands stand between northern Madagascar and the African coast. Two of them, Mayotta and Johanna, are well dissected and embayed and will be described in later sections; two of them are young and nearly reefless. One of these is Comoro, BA 563, 36 by from 9 to 12 miles across, with an undissected cone in its southern part rising to 7874 feet; many lava flows lie on its slopes. Horsey says its coast has not a single good anchorage (1864, p. 259); Voeltzkow reports that the island has no surface streams and that vessels touching there find it difficult to secure a supply of fresh water (1904, p. 280). A few fringing reefs are charted around it. The other young island is Mohilla, BA 563, 17 by 9 miles, 2950 feet high; it has a few fringing reefs and some indications of a 20-fathom bank about 2 miles wide.

The Reefless Island of Réunion

General Account; Cliffs and Valleys

Réunion, also known as Île de Bourbon, in the southern Indian Ocean, BA 1497, measures 33 by 27 miles and is 10,069 feet high. It is one of the most instructive islands in the coral seas. The facts here presented concerning it are gleaned from accounts by Maillard (1862, 1863), Vélain (1876), Drasche (1878), Keller (1898), Garsault (1900), and Cordenoy (1904); of these, Drasche's monograph gives the most geological information. The island is a fine example of a volcanic doublet, the two parts of which are closely welded together in a mass of oval outline with harborless shores. The younger and still active volcano rises in an undissected cone, 2625 meters in height, on the southeast; its exposed shore, where the trade-wind surf strikes with full force, is slightly cut back in low and ragged cliffs apparently not yet provided with beaches. The larger cone, estimated to have been originally 4000 meters in altitude but now reduced by erosion to 3069 meters, is deeply dissected by three main consequent valleys, between which three buttress-like sectors rise toward but do not reach the island center. The sectors are moderately dissected on their exterior slopes and fall by abrupt lateral descents into the separating valleys. The streams are of torrential habit and sweep much detritus into the sea. The coastal margins of the three sectors into which the older cone is divided, constituting three-quarters of the entire island circuit, are cut back in high, mature cliffs. The narrow beach that lies along the cliff bases widens into strand plains, 6 or 8 kilometers across, opposite the three main valleys. A detrital cuspate foreland of gravel and sand has been prograded at the northwestern or leeward end of the island; an artificial harbor, excavated in this foreland, gives the only protected landing place in the coast. Soundings show a bank, with depths of 40 or 50 fathoms half a mile out from the cliff-base beaches; but opposite the prograded strand plains depths of only 20 or 30 fathoms are found a mile from shore.

The little streams, by which the exterior slopes of the three sectors are more or less trenched, have steep if not hanging mouths where they notch the shore cliffs; but the three larger streams which divide the sectors appear to have somewhat aggraded valley floors, even near the shore where the widening sectors reduce the floors to least width. From this it may be inferred either that slow subsidence, not fast enough to drown the beaches, has been in progress or that the valleys have been partly eroded with respect to the lowered ocean of the Glacial epochs. The second inference must not be carried far, because the small amount of valley deepening on St. Helena with respect to the lowered Glacial ocean suggests that such valley deepening in Réunion also must be of small measure. It may be more reasonably inferred that the waves of the lowered Glacial ocean wore down the Preglacial rock platform and its detrital embank-

ment in part or whole by some 20 or 30 fathoms below normal level; for wave abrasion is ordinarily more active than stream erosion. In this case it must be further inferred that, as the ocean rose, not only were the deepened valleys filled but also that as much of the normal platform as had been cut away to low level was built up again with detritus in order to form the existing offshore bank; for the bank seems to be as a whole well graded with respect to wave action at present ocean level.

Prevailing Absence of Encircling Reefs

Coral reefs are imperfectly developed around Réunion. This may be in part because of unfavorably low temperature in the earlier part of Postglacial time, in which case the island should be placed in the marginal belt of the southern Indian Ocean; but this placement cannot be safely made in the absence of a larger number of islands in the region. Or the absence of reefs may be wholly because of the unsuitable foundation offered for reef growth by loose detritus. In any case, reefs are altogether wanting around the ragged shore of the younger cone and off the broadened strand plains of the older one; they occur discontinuously on or near 9 slightly salient stretches of cliffed coast, but their total length is only about 25 kilometers, or less than one-eighth of the island circuit. Réunion is therefore strongly unlike the neighboring but much older island of Mauritius, which has in part a double reef girdle; an emerged reef of earlier date standing from 20 to 30 feet above sea level and a fringing or offshore bank reef surrounding much of the coast at present sea level.

The main fact as to Réunion stands out clearly: The littoral conditions now offered by this submature volcanic island are unfavorable to the formation of coral reefs, because of the prevalence of movable, stream-washed and wave-spread detritus around its shores. The principle here involved would be better established if other islands could be cited in the same fairly well advanced and yet reefless stage of erosion and abrasion; but unfortunately Réunion appears to be in this respect almost unique. It nevertheless illustrates very satisfactorily the principle stated in Chapter III regarding the absence of reefs around islands during the earlier stages of their dissection.

Completely Truncated Volcanic Islands

The question may be raised, in view of the success with which the waves of the open ocean have now been shown to attack undefended volcanic islands, whether some such islands have not stood still long enough in the coral seas to be completely truncated, instead of seeking safety from such a fate by subsiding, as if in order to allow protecting reefs to grow up around them. As far as I have read, very few examples of complete truncation have been described, and three of them are extremely doubtful. These are Mango, Thithia, and Tuvuthá in eastern Fiji, which will be

later described in the chapter on elevated reefs. Sections of these islands given in a report prepared for Agassiz by E. C. Andrews (1900) show later lavas and raised reefs resting on an evenly truncated volcanic mass; but the surface of truncation is drawn a little below sea level and must therefore be a matter of inference rather than of observation. As far as I could see during a brief visit to Mango and as far as can be learned from Andrews' text accompanying his section, no good reason for inferring the truncation is forthcoming. In view of Andrews' residence in Sydney, N. S. W., and of the publication of his report in Cambridge, Mass., the question may be raised whether the redrawing of his outlines there for reproduction in color did not give the submarine structures a greater definition than he had intended. The section of Mango is, however, copied in black and white by de Margerie in "La Face de la Terre," the French translation of Suess' "Das Antlitz der Erde," where it is naturally enough accepted as authentically showing that the surmounting structures are based upon a truncated foundation of volcanic rocks.

Another similar section is that of Bermuda as drawn by Pirsson (1914), to whose article reference has already been made in the chapter on the marginal belt of the Atlantic. The limestones of the island are shown in Pirsson's section as resting at a moderate depth below sea level on a perfectly truncated volcanic cone, although the existence of a submarine volcanic foundation is proved only by a single boring, with which any one of various other volcanic forms would be as consistent as the highly specialized form of an evenly cut-off cone. Indeed, a hilly form of incomplete erosion and truncation is, judging by what is known of many other volcanic islands, of more probable occurrence than a completed surface of truncation. Hence it is likely that the depth at which volcanic rocks were first penetrated in the Bermuda borehole is not the least depth at which such rocks occur there. The probability of this is increased by the strong variations of magnetic declination discovered on the island by Cole (1908).

A fourth example of a completely truncated volcanic island is as well assured as the four above cited are doubtful, because in this case the island has risen since its truncation. It is Mangaia in the Cook group of the South Pacific, which was described fifteen years ago by Marshall as having a "well developed marine erosion surface forming the summit of the island 660 feet above sea level" (1911b, p. 144). A later visit to the island by the same observer demonstrates that since uplift the surface of truncation has been maturely dissected; that since dissection the island has subsided; that during subsidence a barrier reef was built up around the island nearly as high as the surface of truncation; and that the composite structure has been recently uplifted. It is the best known example not only of a completely truncated volcanic island, but also—and this is more significant in the present connection—of a barrier reef that has demonstrably been formed by upgrowth during the subsidence of its

island foundation, as will be made clear in a later chapter. Examples of nearly truncated islands are to be found, according to Chubb, in the Marquesas group, as already told. No examples of uplifted, reef-bearing volcanic islands are known in which the reef limestones rest on a surface of complete truncation as Wharton's theory of atolls demands; but a number of uplifted reef-bearing islands are known in which the volcanic foundation appears to have forms due to subaerial erosion, and to have been covered by reef limestones unconformably during island subsidence.

Summary

Apart from islands concerning which information is scanty, 36 well defined conical islands, most of which appear to be young volcanoes and all of which appear to be of volcanic origin, are cited in the preceding pages. A large majority of them, 26 in all, are essentially reefless; 9 have discontinuous and narrow fringing reefs, which are likely to be lost if no subsidence takes place; for the valleys of these islands are as yet imperfectly developed, and erosion is destined to go on much more rapidly in the future when the stage of Réunion is reached. It is not to be doubted that these young islands must lose a great volume of detritus before they assume the maturely dissected forms characteristic of most barrier-reef islands. All this detritus will be delivered to the shore, where the coarser part of it will form circuminsular beaches; and as the beaches broaden any incipient reefs will be smothered. Abrasion will then proceed unhampered.

Although the older, northwestern cone of Réunion has been strongly cut back in high cliffs around its exposed shores, the loss of area that it has thus suffered is much less than the area that survives. Hence that island should be taken as an example of a cone that has been only moderately consumed by abrasion during a period of still-stand or slow subsidence. It will evidently continue to be for the most part reefless as long as it stands so nearly still and suffers active abrasion; but, if it should subside sufficiently to drown its beaches and to embay its valleys, reefs might then be established on the quiet-lying cobbles offshore or on the face of the plunging cliffs. If subsidence should continue, the fringes would grow up and become an offshore barrier. The future stages thus imagined for Réunion are admirably represented by Tutuila in Samoa and by Tahiti in the Society group. The cliffs of these two islands now plunge below sea level. One has cliff-face fringing reefs, the other has an offshore barrier, as will be described in later sections. Thus it appears that Darwin's leading process of subsidence is not only competent to cause the transformation of fringing reefs into barrier and atoll reefs but that it is also an important if not an essential aid in the preliminary establishment of persistent fringing reefs on volcanic foundations.

CHAPTER XI

VOLCANIC ISLANDS WITH PLUNGING CLIFFS AND EMBAYED SHORE LINES, WITH OR WITHOUT BARRIER REEFS

Outline of Inquiry

The theoretical history of a subsiding volcanic island in the coral seas, as presented in Chapter VI, assigned it an introductory non-submerged and reefless stage, during which its simple shore line should be cliffed; a youthful stage, when subsidence partly submerges its cliffs, embays its valleys, and permits the establishment of fringing reefs; a following stage, when, if the continued subsidence be not too rapid, the fringing reef grows up as an encircling barrier reef; a mature stage, when continued subsidence has completely drowned the early-cut cliffs and has submerged the slopes above them so that the inter-bay spurs taper down into the widening barrier-reef lagoon; a late stage, when the island is so nearly submerged that it is reduced to a few islets and when its barrier reef therefore becomes an almost-atoll; and a stage of extinction, when the island has completely disappeared and the encircling reef becomes an atoll. The preceding chapter gave examples of the introductory reefless stage. The chapters now following confront the theoretical expectations as to the later stages of island development with the facts of coral-sea islands.

We have to consider in the present chapter a number of youthful islands which exhibit plunging cliffs between embayments but are either without or with barrier reefs. The next chapter will present a few additional examples which have non-cliffed, tapering spurs between their embayments but are still without barrier reefs. The islands of these two chapters are set apart from the introductory non-submerged examples of Chapter X because the embayments here found show that submergence has begun; and from the mature examples of Chapter XIII because, in spite of partial submergence, either the shore cliffs are not completely submerged, as in the case of the islands of the present chapter, or because, even after the inferred cliffs are drowned, no barrier reefs have been formed, as in the case of the islands to be treated in the next chapter.

If the Marquesas Islands had not been placed in the eastern marginal belt of the Pacific, they would be instanced here, because they have plunging cliffs between their embayed valleys. Tutuila in Samoa will therefore be the first example here adduced, as it is believed to have plunging cliffs but is without a barrier reef; Tahiti will follow, as it has pronounced plunging cliffs and is surrounded by a well developed barrier reef. The northeastern coast of the long island of New Caledonia will

also be introduced here, for, although it is not a volcanic island but a continental fragment, it resembles Tahiti in having plunging cliffs and a barrier reef. It is to be regretted that no more examples of plunging-cliff islands are found in the coral seas; but in their absence all the more attention must be given to the few that occur.

Tutuila, Samoa, and Its Circuminsular Bank

The American island of Tutuila in the Samoan group, HO 2924, 20 by from 1 to 5 miles, 2141 feet high, offers many problems of interest. It has been visited and described by Couthouy (1844), Wilkes (1845, Vol. 2, pp. 70, 72, 87), Dana (1849, p. 310), Krämer (1897, p. 49), Mayor (1917, 1918a, 1920), Daly (1920, 1924), and R. T. Chamberlin (1921, 1924). Its physical features are exceptionally well shown on the chart above noted, on which the dissected and embayed island is represented by 100-foot contours, and a circuminsular shelf or bank from 1 to 3 miles in width is shown to exist by a great number of soundings of from 30 to 68 fathoms, with a marginal depth of 50 or 60 fathoms. Here, almost as surely as at Palawan in the Philippines, the absence of a visible barrier reef at present sea level is due to the submergence of an earlier-formed barrier reef by rapid subsidence, perhaps aided by Postglacial ocean rise.

Like the much younger island of Savaii and like Upolu apparently of intermediate age, both standing farther west in the Samoan group, Tutuila is a composite volcanic structure. It is believed to be of greater age than its neighbors because it is more elaborately dissected and to have suffered more subsidence because it is more embayed. Chamberlin describes the island as "but a skeleton of its former self, much reduced in altitude [by erosion and subsidence] and covering less than half of its original area"; he adds that it has a tortuous backbone ridge, from which lateral spurs make out between short streams of rapid fall with many cascades (1924, pp. 176, 147). The island is not, however, so well skeletonized as Kakeroma (Fig. 86), in the Riu-kiu group southwest of Japan, or as Norman in the Virgin group in the Lesser Antilles.

The largest embayment, that of Pagopago harbor, enters from the south and nearly severs a smaller eastern from a larger western part of the island. The width of the western part has been increased on the south by recent lava flows, which there form a shore plain two or three miles across and thus attach an otherwise isolated, bay-holding crater to the main mass. The detached cone-and-crater of Aunuu rises from the bank south of the eastern end of the island. The greater part of the southern shore has a fringing reef up to a quarter mile wide; fringing reefs are less developed on the northern shore.

The circuminsular bank is believed to be underlain by a rock platform extended by a detrital embankment, which were abraded and built when the island, standing 300 or 400 feet higher than now, was unpro-

tected by reefs in its youth. The shallower parts of the bank are near its inner and outer margins; the greater depths of 60 or more fathoms lie in an intermediate belt. These variations have been accounted for by supposing that a broad barrier-reef flat of small thickness has been built up on the outer part of the inferred rock platform and that a series of fringing reefs and delta flats have been built out on the inner part. The occurrence of submerged reefs is strikingly attested by the presence of limestone

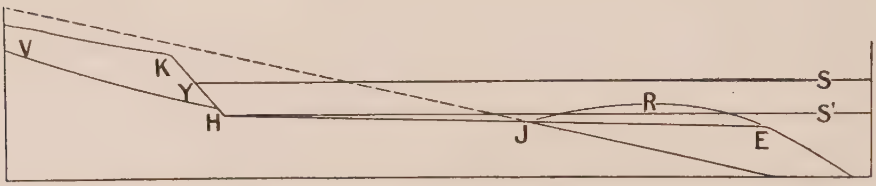


FIG. 106—Inferred profile of Tutuila, showing cliff and platform cut when the island stood higher than now.

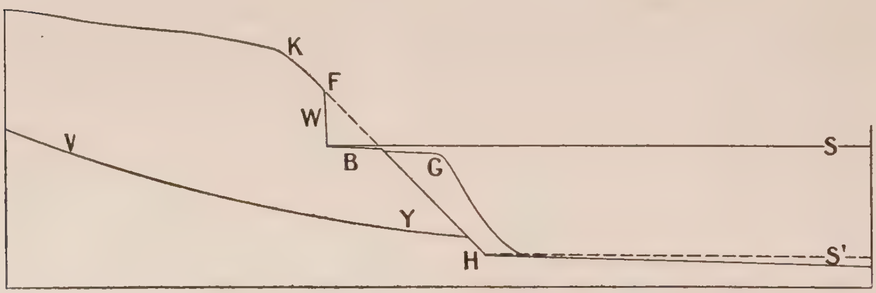


FIG. 107—Present profile of Tutuila, on a larger scale than Figure 106, showing wall and bench cut in spur-end slopes, fronted by fringing reefs.

blocks in the lavas of the two younger offshore craters. The absence of reef protection during the time of platform cutting may be accounted for, as in the present case of Réunion, by the abundance of detritus that was then washed down to the shore from numerous valleys while the young island was stationary or very slowly subsiding. The growth of a reef on the platform may be explained as a consequence of an effective beginning of the submergence which eventually gave the island its present depressed attitude. The drowning of the reef may be explained as the result of accelerated submergence, perhaps associated with Postglacial ocean rise. The total amount of submergence is so great that it must be due chiefly to subsidence.

Manifestly, if a platform, *HJE*, Figure 106, a mile or two wide were cut and built around Tutuila during its early stage of greater emergence, when sea level was at *HS'*, strong cliffs, *HK*, should have risen from the inner platform margin. At the back of so broad a platform the cliffs should have been slanting rather than vertical; and in view of the moderate slope of the island spurs the height of the cliffs may not have been over 500 or 1000

feet. They would have been interrupted by many valleys, *VY*, but the valley mouths should not have been cut down to the platform level. The platform and its barrier reef, *R*, are now beyond the reach of observation, yet their existence is a matter of reasonable inference. But one may, on the other hand, suppose that the circuminsular bank represents a submerged barrier reef and lagoon floor, built up in considerable thickness from a slightly abraded volcanic slope, now deeply submerged. This would demand a much greater subsidence than would be sufficient to drown a broader and shallower rock platform. No recent observer of the

Fig. 108—Wall-and-bench cut in spur-end slope, Tutuila. (Outlined from photograph by A. G. Mayor.)

island has adopted this view; hence, although it is not by any means unreasonable, it will not be further considered here.

If the inferred slanting cliffs at the back of the circuminsular platform were from 500 to 1000 feet high and if the total subsidence by which the platform has been submerged amounted to 400 feet, the upper part of the slanting cliffs, *FK* (Fig. 107), ought still to be seen above present sea level, *BS*. The recognition of the spur-end cliffs would be easier if a good part of their supermarine faces had not been effaced, since their partial submergence, by the abrasion of flat rock benches, *B*, backed by nearly vertical walls, *W*, some of which according to Mayor (1920) have a width of up to 250 feet and a height of from 300 to 500 feet. The relation of wall height and bench width indicates that the spur ends in which the walls and benches are cut must have had a slant of rather more than 50°. Some of Mayor's photographs seem to exhibit, above the new-cut walls, an uppermost acclivity of such a slant, as in Figure 108; for the slanting spur ends, *FK* (Fig. 107), above the walls, *W*, are of much steeper ascent than the gradual rise of the spurs, which lead far inland, back of *K*. These items of fact confirm the expectation expressed above that slanting cliffs,

rising from the inner margin of the submerged platform and notched by waves near present sea level, still show the upper part of their high faces above the new-cut walls. Unfortunately, none of the recent observers of Tutuila have considered this significant point.

A recent and slight emergence (Fig. 108) has placed the new-cut spur-end benches about ten feet above sea level—an emergence which Daly attributes to a eustatic fall of the ocean (1920; 1924, p. 125). Since then, fringing reefs, *G*, Figure 107, which were probably still in an embryonic stage on the plunging cliff faces before the slight emergence, have been built out to a width of from 300 to 1000 feet on the bay sides but to a less width around the spur-end benches. This gives further evidence of a steep submarine spur-end slant, representing the submerged or plunging part of the platform-backing cliffs and corresponding to the inferred supermarine spur-end slant in which the benches and walls have lately been cut. A boring made under Mayor's direction in a fringing reef on a bay side gave the reef only a small thickness, thus showing that the underlying valley-side slope was of moderate declivity. A boring made through the reef outside of the spur-end benches should expectably show a steeper spur-end slope; but no such boring has yet been made.

As in the Marquesas, the flatness of the newly-cut rock benches on the Tutuila spur ends indicates, according to the explanatory scheme of Figure 49 presented in Chapter VI, that the submergence, by which the depressed attitude of Tutuila was assumed before its recent slight emergence, had a relatively rapid final movement and a prompt ending. A submergence thus characterized is better explained by island subsidence than by the climatic rise of the ocean in Postglacial time. On the other hand, a longer interval of time seems to have elapsed since the subsidence of Tutuila than since that of the Marquesas; for the benches cut in the Marquesas headlands are relatively narrow, while at Tutuila the benches are fairly broad. Hence the subsidence of the latter island was probably closed at a somewhat earlier date than that of the former. But this comparison will not hold good if the rocks of the two islands are of significantly unlike resistance. The much less development of fringing reefs around the Marquesas Islands than around Tutuila cannot be safely used in the above comparison. It may be explained by a delay in the Postglacial attainment of reef-supporting ocean temperatures around the Marquesas, or by a delay in the Postglacial arrival of coral embryos there.

The reefs of Tutuila appear to exemplify in a remarkable degree certain consequences of Darwin's theory, in spite of adverse opinions announced by some observers who have visited the island. For example, Mayor concluded (1920a, p. 187) that "the Darwin-Dana theory does not apply to Tutuila," because the submerged barrier reef did not begin as a fringing reef on the unaltered slopes of the island; but this statement implies a misconception. Darwin fully recognized the possibility that platforms cut around volcanic islands might serve as reef foundations and made no

application of the idea only because none of the islands that he knew were rimmed with platform-backing cliffs (1842, p. 49).

Mayor also objected that the submerged barrier reef of Tutuila does not exemplify Darwin's scheme in which barriers are developed from fringes, because the submerged Tutuila reef did not begin as a fringe on the island shore but as an offshore reef on the abraded platform; but this again implies a misconception. For, according to Darwin's classification, reefs that began their growth offshore on a shallow bottom were included with onshore growths as fringing reefs (1842, p. 52). That feature of his classification does not seem well grounded today; but, whether well grounded or not, the offshore reefs which it included with onshore reefs in the fringing class appear to have been precisely the kind of reefs from which the submerged barrier reef of the Tutuila bank was developed.

In still another respect Tutuila offers a striking illustration of the correctness of Darwin's views; namely, in the formation of the present fringing reef along the new shore line after the drowning of a previously-built barrier reef by rapid subsidence (1842, p. 124). True, as Daly has noted, coral fragments are not found in certain bay-side beaches which are taken to be contemporary in their formation with the abrasion of the spur-end benches; hence it should be inferred that the fringing reef had not gained significant size until after the recent slight emergence of the island. The delay of the reef growth thus suggested may be because it took place on the lower, submerged part of the steep-slanting cliffs which rose from the inner margin of the submerged platform. Thus interpreted, Tutuila is certainly an instructive island. It confirms the deduced early abrasional stage of insular development in the coral seas, as well as the intimate association of reef growth with subsidence following abrasion.

Fotuna in the New Hebrides

Fotuna or Erronan, HO 1996, is an outstanding member of the New Hebrides group, 30 miles to the east of its southern part. It seems to be a young volcanic island of small size, 2½ miles in diameter, with a "table top" 1931 feet high, of unknown origin, possibly an elevated reef. Its shore is of irregularly stellate pattern with distinctly cliffed spur ends but without reefs, and with near-by depths of 10 or 12 fathoms increasing to 40 fathoms a quarter mile offshore. If the island has been stationary during Glacial time and if the depth of water near its cliffs is a consequence of low-level abrasion, it ought to be reef-encircled today, but it is not; hence it has probably subsided so recently that no reefs have yet been formed around it. Previous to that subsidence it should have stood higher than now while its embayed valleys were eroded; and previous to that higher stand it would have stood much lower than now if its "table top" is an elevated reef. Such a degree of instability is not extraordinary for this disturbed region. Evidently, the island is worth investigating.

The Plunging Cliffs and Barrier Reef of Tahiti

The Radial Valleys of Tahiti

Tahiti, HO 2065, the largest of the Society Islands, is a volcanic doublet. The larger cone on the northwest measures 15 miles north-south by 18 east-west and is 7321 feet high. The smaller cone on the southeast, known as the Tiarapu Peninsula, is attached to the larger one by a lava-bed isthmus a mile wide. It measures 10 by 7 miles and is 4341 feet high. Typical inter-cone reëntrants head into the isthmus from either side; they are easily recognized as wholly unlike drowned-valley embayments. Both cones retain a number of short sectors of their original slopes (Fig. 109) little affected by degradation, between the distal parts of their larger, sharply incised consequent valleys (Fig. 110). The short sectors slant up and terminate inward where the valleys, deeper cut and more closely crowded together as they are followed upstream, have reduced the upper part of the originally longer sectors to sharply serrate ridge crests, but this reduction of ridge-crest height is no indication of an original crater rim, for which it has been mistaken. The island has been visited and described by many observers, to whom reference is made in an article in which my own observations are presented in detail (1918), and from which the account here given is somewhat modified and condensed.

The streams of Tahiti have not yet in all cases reached grade in their upper courses, for cascades not infrequently interrupt their flow. The massive central rocks seen in certain valley heads and regarded by Dana as the volcanic stock (1886), have been taken by Seurat to be a last remnant of the crystalline rocks of a central Pacific continent, on which the volcanic cones of the Society group were superimposed (1906). A careful study by Marshall has disproved this view and confirmed Dana's. This observer concluded: "There appears to be no reason to believe that before volcanic activity commenced on the site of Tahiti the ocean floor at that particular spot was in any way different from its nature in the closely adjacent areas," where there are great deep-lying expanses of globigerina ooze and red clay (1914, p. 373).

The Spur-End Cliffs of Tahiti

The outer ends of the short-sector ridges are cut off across the basset edges of many lava flows in circumferential cliffs (Fig. 111) which reach heights of 1000 feet or more on the most exposed parts of the coast; and there the smaller streams fall in cascades from hanging valley mouths. The cliffs are of less height in the isthmian reëntrants, especially in the southwestern one known as Phaeton Bay. They also decrease in height as they are followed around the coast to the northwestern or leeward corner curve of the island, where they are weak or wanting. Rounded hills there slant gently under the lagoon level at a gracefully sinuous shore line. The cliffs elsewhere are ascribed to abrasion at a time when the

Fig. [illegible]—Taiarapu Peninsula, Tahiti, and its sloping, spur-end cliffs, looking southeast. (Photograph by Harrison W. Smith.)

FIG. 110

FIG. 111

FIGS. 110, 111—Cliffed spur ends, east coast of Tahiti. (Photographs by Harrison W. Smith.)

unprotected young island stood higher than now, as will be explained below. Their absence around the leeward corner curve is probably because a triangular foreland of gravels and sands, like that at the northwestern or leeward end of the cliffed island of Réunion today, was there accumulated under the action of longshore currents.

The structure of the island is well disclosed in its valley sides and cliff faces. On this point Dana wrote: "Entering the valleys from the sea

FIG. 112—Embayed and delta-filled valley between cliffed spurs, north coast of Tahiti.

shore, the first thing in the structure of the hill which strikes the attention, is the regular stratification of the rocks, and a dip or inclination toward the sea. The dip varies from three to ten degrees, or, more rarely fifteen. . . . In many instances the slopes of the summit of a ridge [above called a short-sector] correspond with the dip of the subjacent layers" (1849, p. 295).

The Delta-Filled, Drowned-Valley Embayments

The radial valleys of Tahiti have been well embayed by submergence, but nearly all the embayments are now filled with delta plains (Fig. 112). The few unfilled bays are branches of the intercone reëntrant near the isthmus. A restoration of the inferred rock-bottom depth of the larger valleys on the line of the cliffed spur ends indicates that the embaying submergence was at least 400 or 500 feet and very likely more. Hence in view of this measure, as well as in view of the principles involved in the Banks-Helena contrast presented in Chapter VI, the submergence of Tahiti must have been caused by subsidence.

It may be here recalled that biological evidence for the subsidence of

Tahiti has been found by Crampton from his study of land snails. He concludes that "the occurrence of related forms [of the genus Partula] in Tahiti, Raiatea and Moorea means that in former times those islands were connected by land; that the common ancestral stock ranged over the whole land mass; and that its local products differentiated into distinct species after the process of subsidence had isolated the mountains now forming the separate islands" (1916, p. 296). This conclusion is based on the belief, apparently accepted by zoölogists, that the snails cannot have been transported from island to island by any natural agency in relatively recent time. Yet that so great a change of level as is above indicated should have taken place even in so long a period as since later Mesozoic time must seem, to geologists, so extraordinary that they would willingly find some simpler means of solving the problem, perhaps by wind or bird transportation of the snail embryos.

The period of valley erosion on Tahiti must have been also the period of cliff abrasion, for both of these tasks would appear to have occupied a similar portion of time in the recent past. Hence, inasmuch as the valleys are now partly submerged, the cliffs must also be partly submerged even though some of them still rise 1000 feet or more over present sea level. The recent period of erosion and abrasion must, moreover, have been a reefless period; and it must have been somewhat prolonged, for it witnessed the removal of an enormous volume of detritus from the higher parts and from the margin of the island and the deposition of the detritus on the submarine flanks of the two cones. It is not permissible to explain the absence of reefs at that time by a general cause, such as a reduction of ocean temperature; for in that case the neighboring islands of the Society group ought also to be cliffed, and most of them are not. The absence of reefs must have been caused by the abundant downwash of detritus from the mountain valleys, whereby cliff-base beaches like those on Réunion were formed on the shore, to the exclusion of growing corals. It is worth explicit mention that the smaller Tiarapu cone is about as well cliffed as the larger cone of the main volcano; and from this it may be inferred that a young volcanic island of moderate size will furnish enough beach detritus to prevent reef development, as long as subsidence does not drown the valleys in embayments where the detritus may be pocketed.

It is quite possible that the subsidence of Tahiti from its former higher stand may have begun slowly, without putting an immediate stop to abrasion by the prompt initiation of protective reef growth; but the subsidence must have eventually gained such a rate that the beaches were submerged, the valleys were embayed, and the down-washed detritus was detained in the embayments. It was presumably at that time that the barrier reef, which now rises offshore and encloses a lagoon, was first established. Its situation is so far from the cliffed coast as to suggest that it is based on the cobbles and gravels of the detrital embankment outside of the cliff-base rock platform, as shown in Figure 113, for

when these coarser deposits were submerged to such a depth that they lay still, corals could have grown upon them.

The Alluvial Shore Belt of Tahiti

As above noted, nearly all of the valley embayments are now occupied by detrital plains, which as a rule advance far enough outside of the former bays to become laterally confluent in a narrow alluvial lowland around much of the coast (Fig. 112), but not on the windward side of the

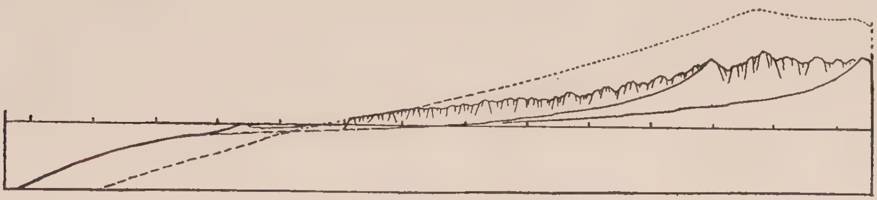


FIG. 113—True-scale profile of north coast of Tahiti and its barrier reef.

Tiarapu Peninsula. The chief town, Papeete, lies on this lowland west of the middle of the north coast. The filling of the bays would thus appear to have accompanied the upgrowth of the offshore barrier reef, both being induced by island subsidence. Various observers have noted that the alluvium of the lowland outside of the circumferential cliff line overlies marine deposits; thus Sawkins recorded long ago that in a well in the northern alluvial belt "five alternate strata of coral and volcanic ashes were bored through in a space of 25 feet" (1856, p. 384). Ribourt (1878) and Setchell (1922) have also reported coral, probably constituting a fringing reef, under the alluvium.

Darwin wrote briefly of the alluvial belt: "The land capable of cultivation is scarcely in any part more than a fringe of low alluvial soil, accumulated round the base of the mountains, and protected from the waves of the sea by a coral reef, which encircles at a distance the entire line of coast" (1840, p. 480).

It was, indeed, this alluvial border which led Darwin to his belief that "although there must have been great subsidence to have produced the barrier-reefs [of the Society islands], there has since elapsed a long stationary period" in Tahiti, and also to the conclusion that "this probably is the ordinary course of events, subsidence supervening after long intervals of rest" (1842, pp. 128, 130). Dana in his time also described the alluvial belt of Tahiti (1849, p. 293; 1872, p. 158) but, curiously enough, without recognizing either the spur-end cliffs or the bay-filling delta plains.

During my visit to the island in 1914 I examined a part of the alluvial shore belt on the northern coast a few miles east of Tahiti, in the neighborhood of a small volcanic salient known as Tahara point. The spur ends thereabouts are cut off in cliffs from 200 to 400 feet high, in good alignment; the larger valleys were cut so deep while the island formerly stood

higher than now that they are entered by arms of the alluvial plain; the smallest valleys, carrying only wet-weather streams, have hanging mouths in the cliff faces. The width of the alluvial plain varies according to its supply with detritus by the outflowing torrents; it advances over 1000 feet from the cliffs in Point Venus, where Captain Cook observed the transit of that planet; but a little west of Tahara point it is hardly wider than 300 feet, and its front is there cut back in a low scarp, 5 or 6 feet in height, below which is a beach of fine black sand. Then comes the lagoon, from 10 to 13 fathoms deep, imperfectly enclosed by a discontinuous barrier reef about half a mile offshore. Outside of the black sand beach are several cusps of a black rock which proved, when I waded out to them, to be indurated volcanic sands lying on a gray coral rock a little below sea level.

This was interpreted as meaning that the latest subsidence of the island had been too rapid to be accompanied by delta outgrowth and that in the first phase of the still-stand after the subsidence fringing reefs were formed along the face of the plunging cliffs; but that during the continuance of the still-stand the detritus brought down by the streams in time filled the valley embayments and then advanced upon the fringing reef and smothered it. Barrier reef upgrowth offshore presumably accompanied fringing-reef growth on the cliff faces; and it must have been in the quiet waters of the barrier-reef lagoon that the alluvial plain advanced beyond the fringing reef, before it was cut back in the present bluffs. The detrital outwash may have become abundant enough in certain parts of this district to be drifted across the lagoon in such quantity as to impede the growth of corals on the outer face of the barrier, particularly near its passes; whereupon the barrier would be more or less worn away by the surf; the passes would be broadened into breaches; and the front of the alluvial shore plain would then be cut back by the strengthened lagoon waves in low bluffs, such as those near Tahara point. A similar change from former outgrowth of the alluvial plain to a moderate retrogressive abrasion was thought to occur in other parts of the same district. Hence it may be that this stretch of the Tahiti barrier is already threatened with destruction, long before the lagoon is converted into a mature reef plain, such as is illustrated in Figure 53. If this be true, it would appear that the smothering and abrasion of a barrier reef need not wait until its lagoon is filled with advancing deltas but may begin at a much earlier stage of delta growth; indeed, whenever stream floods provide such a quantity of silt-laden fresh water that it is drifted across the lagoon to the reef in a damaging amount.

The above interpretation seems to account for facts concerning the Tahiti barrier recently reported by Crossland (1927). He believes that the imperfect reefs off the northeast coast of the island have lost the upper five fathoms which formerly brought them to the surface and suggests that the change from earlier reef upgrowth to present reef abrasion is a consequence of the "laterisation of the basalt" on the mountainous island,

and "its conversion from hard rock to that red clay so conspicuous on the slopes, which in floods causes all the streams to run red." The still-stand encroachment of volcanic detritus, whether lateritized or not, upon the lagoon seems a sufficient explanation of the change. Crossland continues: "In Tahiti . . . it is clear that the age of corals is past" and then asks: "Is it possible that this is true of the world in general?" This seems to me greatly to exaggerate a relatively subordinate matter. The barrier reef in certain parts of its circuit around Tahiti has the form of a broad flat, which has so far encroached upon the lagoon as to reduce it to small width. Clearly, those parts of the barrier are vigorous enough not to be reduced to subsurface reefs by the abrasion of their upper five fathoms. And even though "the great flood of January, 1926, caused wholesale death of the corals inside of the lagoon," as Crossland reports, the lagoon corals will pretty surely reëstablish themselves, as they must have done after similar floods in the past. The weakness of the northeastern part of the barrier would seem to be a local matter and probably a recent and temporary matter also; for the largest valley, Papenoo, of the island opens there and builds the largest delta flats out into the lagoon; and moreover a slight renewal of the subsidence, to which the original establishment and later upgrowth of the barrier appear to have been due, would free it from invasion by flood detritus and almost surely restore it to full strength again. It may be that the decreased area of growing coral on the face of the northern reef in the quarter-century period between the observations by the *Challenger* and by Agassiz, as further stated below, suggests a very recent date for the initiation of reef abrasion.

Tahiti as a Physiographic Type

Tahiti deserves to be highly regarded by physiographers, for it has been suggestive of new physiographic ideas to various visitors. It was on this island that Darwin was first led to conceive the origin of insular valleys by stream action instead of by marine erosion during the supposed emergence of the island by upheaval, as he had before supposed; but he still held to the idea that the volcano had been formed under the sea and then upheaved. He wrote that the cone, "after being raised, has been cut by numerous profound ravines, which all diverge from the common centre; the intervening ridges being flat-topped, and belonging to one slope" (1840, pp. 483, 484). The "flat-topped" ridges here mentioned are evidently the unconsumed short sectors of the original volcanic slope, as above described. Farther inland he saw the "knife-edged ridges, having on each hand profound ravines." In the Cordillera of the Andes he had "seen mountains on a far grander scale, but for abruptness, no part of them comparing to this" (1840, p. 487). It is singular that a larger application was not made of this understanding of the erosional origin of valleys; for, even before reaching Tahiti, he had seen evidence of great erosion in the Andes and of correlatively great deposition in Patagonia.

During an ascent of Bell Mountain in Chile, 6400 feet high, he moralized on "the countless ages which it must have required, to have broken through, removed, and levelled whole masses" of the mountains; and he there recalled that when he saw the vast shingle beds of Patagonia, he had "wondered how any mountain chain could have supplied such masses, and not have been utterly obliterated." He added: "We must not now reverse the wonder, and doubt whether all powerful time can grind down mountains—even the gigantic Cordillera—into gravel and mud"; and a few pages later he almost anticipated Powell's dictum that mountains are ephemeral forms by briefly noting: "Mountains suffer degradation and wear away" (1840, pp. 314, 325). Had his attention not been directed during many following years to explaining the evolution of organic forms, he might well from so early a beginning have become the leader in explaining the evolution of land forms instead.

Dana was early impressed by the sharpness of the radial ridges of Tahiti between the close-set, deep-cut valleys as a consequence of stream erosion. Forty years after his Pacific voyage he described the island, under the name of "Otaheiti," as the type of a well dissected volcano (1886). But his chief physiographic discovery on Tahiti was made during an ascent of Mt. Aorai, one of the central peaks, in 1839 when the idea came to him that the subsidence of a dissected island would give it an embayed shore line (1849, p. 393). He thus for the first time in the history of science recognized this fundamental principle of shore-line development. Yet, curiously enough, he did not perceive that precisely such a sinking of Tahiti had actually taken place but that it took place long enough ago for the deep bays to have been filled by delta plains. He later excluded subsidence by noting that "Tahiti presents none of the Marquesan evidence of subsidence. Its erosion-made valleys . . . die out at the broad shore plain and the island is comparatively even in outline" (1885, p. 93). His failure to recognize the valley plains as filled embayments must have been due, in part at least, to his not having seen the several small, drowned-valley bays which enter the Phaeton reëntrant on the south coast and which are not yet filled because the streams that flow into them are exceptionally short. The two bays mentioned by Dana on the north side of the island are not drowned valleys but are mere unfilled spaces between delta salients of the alluvial lowland that encroaches upon the lagoon waters.

It is difficult to understand why Darwin and Dana and various other early observers, who must have been familiar with the occurrence of wave-cut cliffs around other volcanic islands, did not recognize the occurrence of similar cliffs on Tahiti. Darwin said nothing of them. Dana implied that they are nonexistent; for, although he originally described the island as "mountainous quite to the water's edge in a portion of its circuit" (1849, p. 293), his later statement, probably written from a nearly 50-year memory instead of on the island itself, is that "high narrow

ridges . . . alternating with gorge-like valleys 1000 to 3000 feet deep, radiate from the central peaks but die out in a broad even plain at the shores" (1885, p. 92). A more recent observer, Marshall, makes explicit denial of the occurrence of cliffs; he says: "It is evident that if the coral reef rises on the edge of a platform of marine erosion this very erosion would have worn the spurs back in such a way that they would terminate in steep cliffs. In no instance at . . . Tahiti that the author observed did the spurs have an abrupt termination. The lower slopes of the islands are in all cases notably less steep than the upper slopes" (1911a, p. 13; 1911b, p. 142). The latter statement holds true as between the steep central peaks and the slanting spur sectors; but not as between the slanting spur sectors and the cliffed spur ends.

Agassiz seems to have been the first observer to recognize the spur-end cliffs of Tahiti and to explain them as the work of waves. He wrote: "The high steep slopes and bluffs which fringe the island are cut by innumerable deep valleys penetrating almost to the centre. . . . On the eastern [windward] face numerous waterfalls are seen, many of them falling [out of hanging valleys] from great heights. . . . On the northern face of the island the slopes are more gentle." Around the southwestern curve of the larger cone, "the steep cliffs rise more than two thousand feet and slope directly to the shore"; but here the cliff faces are much battered by ravines of incipient dissection. "The eastern and northern coasts of the [Tiarapu] peninsula are flanked by steep bluffs rising almost vertically from the sea, to a height varying between twelve and fifteen hundred feet" (1903a, pp. 143, 148). The cliffs are recognized also by Setchell (1922) and Crossland (1927).

The form and the situation of the cliffs are such as to leave no question of their origin by wave attack; but it must be understood that the attack was made at a time when the island stood several hundred feet higher than now. The lower faces of the cliffs are submerged, and, although the visible faces are steep, they are by no means vertical. It may be for this reason they have been so generally overlooked as sea cliffs. Their angle of slope may sometimes be 60°, and perhaps more on the exposed eastern coast of the Tiarapu Peninsula, but it is usually less. The original steepness and evenness of the upper faces of the cliffs have probably, since partial submergence, been somewhat decreased by erosion, now that wave attack upon them has been held off by the barrier reef and the alluvial plain.

Like Agassiz, Crossland, who has recently spent a year on the island, regards the shore cliffs as having been cut back at present sea level. He rejects the interpretation of the broad, gravel-covered floors of the valley mouths as embayments produced by subsidence and filled by delta plains and says in this connection that the valley floors are not "level, all the streams having a rapid flow throughout their course" (1927a); yet that is precisely as it should be when drowned-valley embayments are filled with the delta plains of torrential streams. He prefers to explain the valley-

mouth plains as the result of lateral stream erosion on a still-standing island and therefore concludes that the Tahiti reefs "have attained their barrier form without subsidence." This explanation seems to me inadequate on several grounds. First, if the lower part of the valleys had been so much widened by lateral erosion, the upper parts could hardly have preserved the sharp V cross profiles that still characterize them. Second, the greater depths of the lagoon, 20 fathoms or more, show that no shallow platform of volcanic rocks extends seaward from the visible bases of the spur-end cliffs, as it should if the cliffs had been cut at present sea level. Third, the strong embayments in five other members of the Society group, to be described in Chapter XIII, are competent witnesses for subsidence, which is therefore probable for Tahiti also. Fourth, the complete filling of nearly all the Tahitian embayments, while the embayments of the five other islands are very incompletely filled, is a natural consequence of the greater area and height of Tahiti.

Fifth and most significant, several small, unfilled bays are, as above noted, to be seen on the southwest side of the isthmus between the two cones of Tahiti, two of them to the west of the narrowest point and one to the south (this one closed by a bar across its mouth). They are manifest examples of partly submerged valleys; they are little filled with deltas because their streams are short and small; they show very clearly that all the other valleys of the island would likewise still contain water bays, if their streams also were small, instead of being mountain torrents. The small bays that so clearly indent the isthmian shore line should, of course, not be confounded with the wide-open, inter-cone reëntrants of that shore line, which are, as in the case of Oahu and other volcanic doublets, as manifestly consequent upon the initial form of the volcanic cones as the small bays are consequent upon the valleys that have been eroded in the slopes of the cones. Yet, as if to show how differently the same physiographic features may be looked upon by a zoölogist and a physiographer, Crossland, after first asserting, "There are *no* bays on Tahiti," later recognizes that some bays do exist when he mentions "the little bays that open out of . . . [the southwestern reëntrant of the isthmus]"; but he adds that "they are very peculiar" and "are certainly not drowned valleys" (1927a).

Origin of the Tahiti Barrier Reef

The physical features of Tahiti deserve especial consideration because they offer so good an illustration of the intimate connection between the development of an island's form and the development of its encircling barrier reef. Clearly Tahiti has passed through an early reef-free period of considerable duration, when its high cliffs were cut back and its deep valleys were eroded nearly to their present form; and as clearly it has since then entered upon a period of subsidence and reef growth. Evidently, it was the subsidence of the island that removed conditions unfavorable for reef growth and introduced conditions favorable for reef

growth. In this respect Tahiti represents a possible future stage in the history of Réunion, when subsidence shall take place there also; just as Réunion represents a past stage in the history of Tahiti, before subsidence had become effective.

Hence a sixth and final reason for subsidence, in addition to the five other reasons stated above, is that it provides a simple and effective cause of changing from the earlier, reef-free, cliff-cutting stage in the island's history to the present reef-protected stage, a cause that is consistent with the history of various islands in the coral seas. The failure to explain this change seems to me a serious omission in Crossland's account of the island. He explicitly recognizes "the truncation of the ends of the [volcanic] slopes" by "cliffs cut by the ocean waves"; also the "strip of flat [alluvial] land running around the base of the [cliffed] mountains between them and the lagoons"; and he perceives that the alluvial flats "owe their existence to the coral reefs" which serve as a breakwater and which, as he believes, were once so extensively developed as to be continuous from shore fringe to outer barrier; but he introduces no cause for the change from cliff-cutting to reef-building.

The later reef-growing stage now current on Tahiti must be of decidedly less duration than the earlier, reef-free stage, because the detritus washed down by the streams into the valley embayments during the later period is small in comparison with the total amount of detritus removed from the valleys in the earlier period; and because the detritus that has fallen from the cliffs since the waves ceased attacking them is small in comparison with the total volume of detritus that was removed during the time of wave attack. The later period of subsidence and reef growth therefore constitutes as yet only a short beginning of a second stage in the island's history. For the other barrier-reef islands of the Society group, and especially for Borabora and Maupiti, the second stage has already made a much greater advance.

Let it be noted that the narrowness and discontinuity of the Tahiti barrier, especially around the Tiarapu Peninsula, should not be ascribed either to the violence of the surf that beats there, or to a supposed low temperature of the ocean water. Broad and continuous barriers are found on many other islands where the surf is equally violent; and flourishing reefs, much better developed than those of the Tiarapu Peninsula, are found around two of the Austral Islands, which are well to the south of Tahiti and therefore in somewhat cooler water. The narrowness and discontinuity of the Tahiti barrier on the eastern side of the island should therefore probably be ascribed to unfavorable conditions associated with detrital outwash, as above suggested.

Descriptions of the Tahiti Barrier Reef

The *Challenger* report gives a very explicit statement regarding coral growth on the outer face of the Tahiti barrier, on the northern side of the

islands, as follows: "The whole of the space from the edge of the reef to a depth of 35 fathoms was covered with a most luxurious growth of corals, with the exception of one or two small spaces where there was white coral sand. . . . So irregular was the ground out to 35 fathoms that dredging was almost, if not quite impossible. . . . Beyond 150 fathoms the bottom was a coral sand with volcanic minerals and pelagic shells. The soundings taken by the ship at depths of 420, 590, 620 and 680 fathoms showed the presence of a volcanic sand or mud, containing coral débris" (1885, pp. 779, 781).

Agassiz, visiting Tahiti about 25 years later, said: "I cannot well reconcile the condition of the outer reef of Papieté, as we saw it, with the account given in the Narrative of the 'Challenger'." He found the outer face seldom occupied with living corals to greater depths than 4 or 6 fathoms, "the lower part of the slope being covered with broken fragments of dead corals, or dead corals down to a depth of eighteen fathoms. . . . At about fifteen to sixteen fathoms the masses of dead corals were separated by wide bare lanes of sand, with here and there larger masses, from two to four feet, on the face of the slope" (1903a, pp. 150, 151).

Following Agassiz by a similar period, Crossland, as above noted, finds the reefs of the northern and northeastern coast so little occupied by vigorously growing corals that he regards the reefs as having suffered reduction of size by destructive agencies. If later observation shows that corals do not return there, that part of the Tahiti reef will gain additional interest as exemplifying a condition of reef smothering alluded to on page 132.

Murray's Theory of Reef Outgrowth

Most visitors to Tahiti have followed Darwin and Dana in associating the upgrowth of its barrier reef with the subsidence of the island; yet few of them have given any independent evidence of that subsidence. The *Challenger* report, however, said nothing of subsidence and rejected Darwin's theory of reef upgrowth for Murray's theory of reef outgrowth, as follows: "According to Mr. Murray the observations of the reef at Tahiti support the view that the reefs have been built from the shore seawards, and that the lagoons have been and are still being formed by the removal of the inner and dead portions of the coral reef by the solvent action of sea water. . . . A talus has been formed [exterior to the reef] on which the corals living down to 35 fathoms have found a foundation on which to build further seawards. . . . It is maintained by Mr. Murray that the whole phenomena of the Tahiti reefs may be fully explained by reference to the processes at present in action, without calling in the aid of subsidence as is done by Darwin and Dana" (1885, pp. 781, 782). This theory of the barrier-reef is altogether incompetent to explain the physiographic features of the island surrounded by the reef. It can be accepted only by those who take no account of the evidence given by the island regarding the conditions under which the reef was found.

Agassiz' Three-Phase Scheme

Agassiz also dissented from the Darwin-Dana theory of reef upgrowth in consequence of island subsidence and adopted instead what may be called a three-phase scheme of coastal and reef development. The scheme includes, first, the production of a circuminsular rock platform by marine processes acting at present sea level; then the growth of a broad reef flat upon the platform; and finally the removal of the reef flat now in progress by renewed marine action. As to the first phase, it is stated that "the northeast trades have eroded a wide platform on the east side of Tahiti," on which "here and there an outlier of volcanic rock can still be traced, giving us a clue to the nature of the underlying platform, and plainly showing that it is only the extension of the spurs of the mainland which have been eroded and washed out to sea"; and again that "the wide platform carrying the fringing and barrier reefs of the west side of Tahiti has been formed by submarine erosion" (1903a, pp. 146, 149–150).

Little is said concerning the second phase of reef construction, but it may be inferred from the statement as to the third phase of reef destruction supposed to be now in progress, as follows: "On the northern and southern side of the island, as well as the western face where the trades do not strike with any great violence, the reef flats are broad. But on the eastern side, and also off the southeastern point, where the action of the trades is incessant, the reef flats have been greatly eroded, leaving a wide, deep lagoon, separating the barrier reefs from the main shore. Finally, on the northeastern side . . . the barrier reef has become broken into isolated and disconnected reef patches, all pointing to the existence of a former wide reef platform" (1903a, p. 144).

The dissolution of the former reef flat is explained as follows: "The strength of the [lagoon] currents is . . . due, in great part, to the amount of water which is forced over the sea face of the reef flats by the incessant roll of the breakers. . . . The amount of water which has thus found its way into the lagoons . . . gives us a simple explanation of the mode of origin of the lagoon, formed by the scouring of the tides running parallel with the shore, and by the solvent action of the sea reinforced by submarine erosion. This has gradually changed the wide reef flats, forming at first fringing reefs of great breadth on the northern and southern faces of the island, into such bays [lagoon areas] as those of Papieté and its eastern and western extensions [on the north], and into the lagoons from Teavaraa Pass [in the mid-southern reef] to Phaeton Harbor" [at the isthmus] (1903a, pp. 148, 143–144).

The evidence above given, suggestive of a partial consumption of the northeastern reefs because of the outwash of volcanic detritus upon their corals, gives some support to Agassiz' views but only for a restricted part of the Tahiti coast; it does not seem warranted to extend that evidence all around the island, as his three-phase scheme seems to demand.

One reason for not accepting this three-phase scheme is that no causes are assigned for the change from the destructive processes of the first phase to the constructive processes of the second or from the constructive of the second to the destructive of the third. Another is that, in spite of the explicit statements regarding a shallow rock platform, no sufficient evidence of its occurrence is presented. Furthermore, no sufficient account is taken of the physiographic development of the visible island. When this development is considered, it proves truly that a submarine cliff-base platform is present but also that it has been submerged to a depth much below the level of present wave action. Certain small lagoon islands near the northwestern corner curve of Tahiti are described by Agassiz as "volcanic . . . the remnants of a volcanic platform." I examined these islands with care; they are low and flat; they show no volcanic ledges; they contain little if any volcanic detritus but consist largely of calcareous reef débris. They give no indication whatever as to the form or depth of the volcanic base which they rest upon.

Other reasons against the three-phase scheme are that most of the lagoon now appears to be suffering aggradation rather than excavation and that the greater part of the barrier reef appears to be a growing rather than a wasting structure. Agassiz himself recorded that "the amount of silt which the numerous rivers of Tahiti bring down into the lagoon of the barrier reefs is very considerable; we find the bottom of the lagoons covered in great part with volcanic mud and silt, in the central part of the lagoon and in the neighborhood of the shore, but it is mixed more or less with coral sand as we go toward the outer face of the reef flat near the barrier reef" (1903a, p. 144). Thus deposition rather than solvent erosion would seem to characterize the lagoon bottom. Furthermore, the broad shoals of overwashed coral sand which, dotted with storm-swept blocks of reef rock, slant from the northwestern reef into the lagoon, are altogether inconsistent with the idea that the lagoon is now undergoing excavation.

Crossland here again comes to a conclusion similar to Agassiz'. He writes: "We have conclusive proof that the reef was once continuous [from island-shore fringe to outer barrier] and that the lagoon has been hollowed out secondarily, since we find here and there, on every part of the reef, basaltic stones, lying on the surface, or bedded into the coral rock, which certainly reached the outer parts when there was no lagoon channel at all." The narrowness of the lagoon on the southwest "strongly suggests that earth movements made at first deep fissures in the reef which have become widened into lagoons by the erosion of their sides, which is often so evident" (1927b, pp. 215, 216). But it is difficult to adopt this view. True, "the occurrence of filled-in cracks in the reefs in many places," associated with "subsidences and breakages" in the outer reef would seem to be the preliminary stages of a down-sliding that Gardiner has thought was of importance in many elevated Fijian reefs, as will be

told later; but how the narrow cracks have been widened to a half-mile lagoon is not at all clear. While there is indication that the northeastern reefs are now wasting, as if in consequence of the overabundance of island detritus washed out upon them at time of heavy floods, as above suggested, and while occasional floods temporarily destroy the lagoon corals of the southwestern reefs, as above quoted, the account that Crossland gives of these reefs strongly indicates that they are, on the whole, increasing rather than wasting away. He records that, before the flood of January, 1926, living corals were abundant there "over a wide area" of fringing reef which dropped into the lagoon as a "wall of living coral"; also that the narrow barrier has a "slope of sand" slanting into the lagoon which it encloses and has a "coral growth" down to 10 fathoms on its outer side. Hence the lagoon, which has but small width at certain points on the southwest, would seem to be, in view of the above items of fact, well explained as not yet wholly filled previous to a stage of greater filling, rather than as already partly excavated after such a stage.

If the lagoon were formerly so completely filled with broadened reefs that the island streams swept "basaltic stones" all across the reef flat to its outer margin, half a mile or a mile from the island shore, the gently sloping gravel floors that now occupy the valley mouths must have then been built up or aggraded with volcanic detritus to a significantly higher surface—probably 20 or 30 feet higher at least—and this upbuilt surface must have extended even farther upstream than the present heads of the valley floors in order that the streams should have then, as now, preserved their rapid flow on their cobbly beds in spite of their increased length. There is nothing at all improbable in such an aggradational upbuilding, so far as the streams are concerned; it would indeed have been compulsory upon them if they had had to carry their stony detritus across the broadened reef flat. But if such aggradation were followed by degradation to the present gently sloping surface of the valley floors, while the reef flat was being excavated where the lagoon now replaces it, remnants of the higher detrital surface should still be seen here and there as valley-side terraces, standing distinctly above the present valley floors; low, tabular covers of volcanic detritus should still remain on certain reef-flat patches that now stand in the lagoon near the island shore. Yet, as far as the valleys that I entered and the reef-flat patches that I crossed are concerned, no such detrital residuals were observed; and no such residuals are mentioned by Crossland, who indeed takes no account of this aspect of the problem.

It is, moreover, difficult to understand how the excavation of the lagoon, by whatever agencies were there working to remove the previously formed reef flat more rapidly than the lagoon corals were working to maintain it, could have left, in the penultimate stage of their accomplishment, a series of narrow, discontinuous ridges off the northeastern coast of the island, all standing on a single circumferential line between the ex-

cavated lagoon and the deep ocean, just as a young barrier reef would stand. For, if the aggrading streams built up their gently sloping flood plains so that they could carry basaltic stones all across a former, lagoon-filling reef flat to its outer edge, they must have carried also a great volume of sand and silt, by which the corals on the reef face would have been weakened if not killed; and thereafter the retrogressive abrasion of the outer face of the reef by strong ocean waves would have been much more rapid than the excavation of the lagoon by the weaker agencies there at work. As the broad reef flat was thus reduced in width by stronger exterior attack and weaker interior attack, its penultimate residuals could hardly have assumed the form of narrow ridges with their outer slope descending regularly and rapidly to great depths: the residuals ought to have a shallow platform of marine abrasion in front of them, and their inner face should be irregular, instead of trending parallel to the outer face. Hence, although Crossland concludes that narrow northeastern ridges are not "young reefs which have not reached the surface," it must still be questioned whether they may not be, after all, of small breadth chiefly because of their youth and whether they are not, as above suggested, of recently weakened growth and reduced size because of the outwash of detritus upon them.

The uncertainty of Crossland's explanation seems indeed so great that one must wonder whether the basaltic stones that he found on the outer reef were not carried across the lagoon by the natives instead of washed out there by the streams on aggraded flood plains superposed on lagoon-filling reef flats. For in view of the considerable number of volcanic blocks seen on the relatively small areas that I examined on the barrier reefs of Raiatea and Huaheine, farther northwest in the Society group—where they appear to have served as hearthstones and as canoe anchors—such a means of transportation for the Tahiti stones would seem to deserve consideration, instead of one which demands so great a reversal of processes as is involved in a former reef-flat broadening and flood-plain building all across the present lagoon area all around the island, and a subsequent consumption of most of the reef flat and flood plains; especially as certain expectable consequences of the reversed process are not found. It should be recalled in this connection that the occurrence of slabs of reef limestone on the volcanic slopes of Savaii, which led some observers to infer an upheaval of that island, have been more reasonably accounted for by Krämer as having been carried up from the shore by the natives.

It would therefore seem that the Tahiti barrier reef is probably increasing in size rather than wasting away, except where its growth is weakened by outwashed detritus. It is truly narrower and more interrupted by passes and breaches than certain stronger reefs, for example the great Tagula barrier east of New Guinea. But it is not narrower than certain weak reefs, for example Budd reef in northeastern Fiji, where subsidence appears to have been unusually active. Unless subsidence

ceases, there appears to be good reason for believing that the Tahiti barrier will grow as other barriers have grown and become in time wider and more continuous than it is now. On the other hand, if the present stillstand is unduly prolonged, there is equally good reason for believing that the whole reef will be overwhelmed, as a part of it already seems to be,

FIG. 114—Looking southwest along northwest coast of Tahiti.

with volcanic detritus of which the mountainous island possesses so enormous a store.

Summary for Tahiti

In view of all the facts that I was able to observe on the island itself, and in review of all the descriptions and opinions of others that I have read—including many not cited above—Tahiti qualifies as an excellent witness for the verity of two chapters in the theoretical history of a subsiding volcanic island in the coral seas, as here outlined in an earlier chapter. It presents admirably the expected features of a good-sized island that has been sharply dissected by streams and strongly abraded by waves—like Réunion today—in an earlier and reefless chapter of its post-eruptional evolution, when it stood for a considerable period several hundred feet higher than now. And it presents equally well the expectable features of an island that has recently entered a second chapter characterized by subsidence and reef upgrowth. This second chapter is, however, as yet so little advanced that the shore cliffs cut in the previous chapter are not wholly submerged, except on the leeward corner curve of the island where they were presumably low or wanting, and that the barrier reef, recently initiated, has not yet grown up to a great strength. Tahiti presents also what seems to be the incipient stage of reef smothering by outwashed detritus in part of its reef circuit. The present condition of the growing reef is well shown in a view from a hill at the northwestern curve of the shore line, sketched in Figure 114. The long volcanic slopes, deeply dissected by consequent valleys, end in cliffs, here of much less height than farther south; the valley-mouth deltas are laterally confluent in a narrow, cliff-base alluvial belt, occupied by coco-palm groves to which my sketch does no justice. Then comes the brownish belt of the fringing reef, changing rather abruptly to the rich and smooth blue of the quiet lagoon waters; and the blue merges gradually into the wonderful blue-

green of the water over the inwashed, lobate shoals of white reef sands adjoining the barrier reef. The narrow barrier reef itself comes last and is separated by a strip of white surf from the deep blue of the white-capped ocean that stretches to the horizon. There seems to me no question whatever that this part of the Tahiti barrier is essentially an immature upgrowing reef, initiated by island subsidence after a reef-free stage of island cliffing, although a delay in the continuance of the subsidence is at present apparently permitting the encroachment of outwashed volcanic sands on the northeastern arc of the reef, to the injury of its growth. A slight renewal of subsidence would restore it to a thriving condition.

The Cliffed Northeast Coast of New Caledonia

General Features of the Island

The continental island of New Caledonia, a French possession, HO 2867, 2868, trending northwest-southeast, 225 miles long by 30 or 40 wide, bears a good number of mountains exceeding 3000 feet in height, with the highest summit reaching 5348 feet. It is composed of crystalline schists, serpentine masses, and deformed stratified rocks; but it may be included in the present chapter concerning cliffed volcanic islands, because it has plunging cliffs of steep slant (Fig. 115) along much of its well embayed northeast coast, where a wide lagoon is enclosed by a well offset barrier reef. The contrast between the strongly truncated headlands and the sloping spurs of the bay sides is very marked.

Much attention has been called to the island by reason of the nickel and cobalt ores it contains, as well as by reason of its having been used as a penal colony to which Parisian communists, besides convicts in earlier and later years, were sent in 1871. A monographic account of its geography has been compiled by Augustin Bernard (1895); other articles and reports pertinent to our present inquiry concerning the island have been published by Balansa (1873); Chambeyron, who gives many details concerning the reefs (1875; 1876); Garnier (1867; 1867a; 1871); Heurteau (1876); Lambert, who gives details concerning two small islands at the opposite extremities of the great island where he was stationed as a priest for many years (1900); Le Chartier (1885); Lemire (1884); Compton (1917); and Sarasin (1923). It is surprising to note that none of these observers recognize two cycles of subaerial erosion in the sculpture of the island nor a well-advanced cycle of marine abrasion in the production of the cliffs along the northeastern coast. It is even more surprising to discover that, excepting Compton—with whose companion, Montgomery, I had during a brief meeting at Nouméa in 1914 the pleasure of discussing the bearing of drowned valleys on the coral reef problem—and Sarasin, a more recent explorer of the island, none of the above-named authors recognize a movement of subsidence as indicated by the many embayments of the shore line.

The magnificent barrier reefs around this long island are the greatest insular reefs in the world. They run about parallel to and 5 miles or more distant from the island shores, but extend some 40 and 90 miles beyond its southeastern and northwestern ends, so that their paired length over all is 355 miles. After a blank space of 30 miles on the northwest, the two D'Entrecasteaux atolls go on 40 miles farther. This great longitudinal extension of the reefs leads to the idea that the island was formerly

FIG. 115—High sea cliffs and sloping bay sides on the northwest coast of New Caledonia.

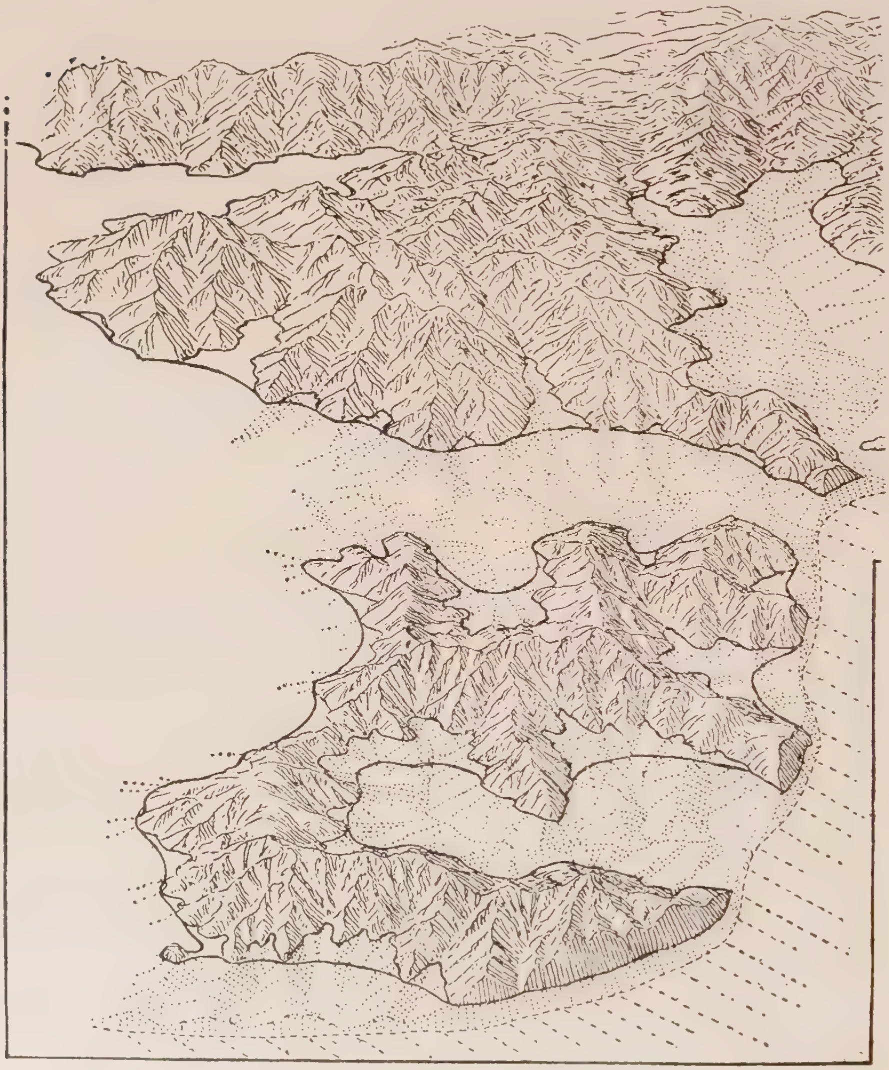
much longer than it is now, and this idea is confirmed by its geological structure.

My visit to the island, which lasted nearly a month, was made the more successful by many kind attentions from His Excellency the Governor, M. Auguste Brunet, and from several residents in the capital, Noumea, on the southwest coast. I made the circuit of the island on trading steamers, following the lagoon for the greater part of the way, and had excellent views of the coast, as, in the absence of lighthouses, travel was usually limited to daylight hours. Only along a stretch of the southern side of the island, where the lagoon is obstructed by emerged reefs, did one of the steamers have to run for a moderate distance outside of the barrier; exit was made through a pass to the open sea, where the reef was a marvelous sight, with the heavy surf breaking in long white lines in either direction. The southeastern end of the island was later studied in detail from a small sailboat. It was there that I found on the adjoining small island of Uen, of skeleton outline, the transition from the plunging cliffs of the eastern coast and southeastern end of the long island, to the non-cliffed coast of the southwestern side: it was immediate and unquestionable, as shown in the lower left foreground of Figure 116.

New Caledonia will be treated again in a later chapter with respect to its well embayed but not cliffed southwestern coast; but these two accounts will be brief, as I have elsewhere described the island and its reefs in some detail (1925a). It may be here noted, however, that it would be difficult to find a better example than is offered by the plunging-cliff, northeast coast of New Caledonia, of the need and the reward of treating land sculpture as a reasonable process and of therefore giving land forms an explanatory description.

The Plunging Cliffs of the Northeast Coast

It is conceivable that the northeastern cliffs are the modified scarp of a great fault, on which a long marginal slab of the island was depressed below ocean level at a sub-recent geological date. But in this case the measure of upgrowth demanded for the barrier reef would be larger than if the cliffs have been produced, as I came to believe during my circuit of the island, by the work of marine abrasion during a former higher stand when the northeast coast was not reef-protected. Under this interpretation the maturely opened valleys, by which the cliffs are repeatedly interrupted, must have been eroded while the cliffs were retrogressively abraded. It



is chiefly because the valleys are now well submerged in branching embayments that the cliffs are believed to plunge to a good depth below present sea level. For the same reason the rock platform, which must have been developed as the cliffs were cut back, is believed to be now well submerged below the small depth at which it was abraded. In contrast to Tahiti, where the embayments are nearly all delta-filled, those of New Caledonia are much less encroached upon by island detritus.

Judging by the breadth of the bay mouths and the declivity of their side slopes, the embaying submergence must measure from 500 to 800

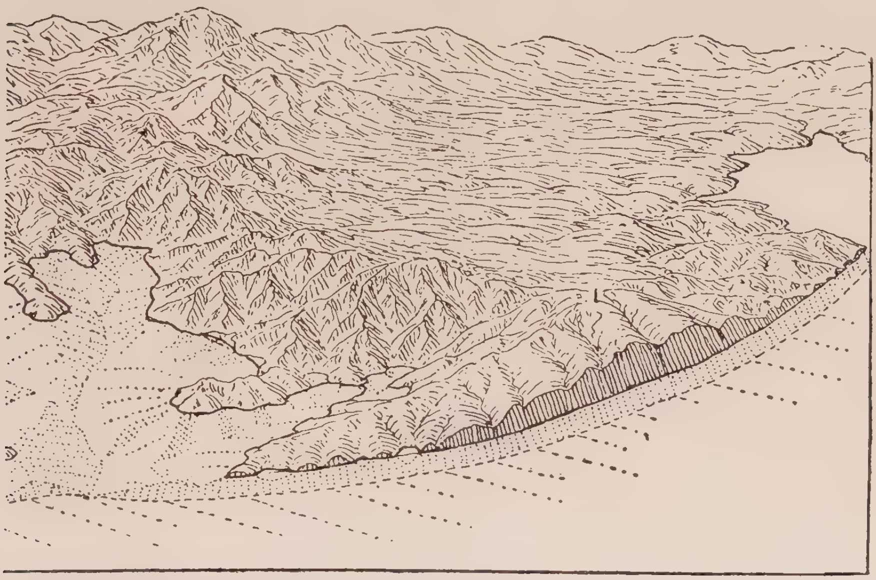


FIG. 116—Schematic bird's-eye view of the southeastern end of New Caledonia and the adjoining island of Uen, showing the transition of plunging-cliff coast to non-cliffed coast.

feet or more, and hence must be ascribed to subsidence and not merely to Postglacial ocean rise. The dimensions of many embayments are so great that they cannot be reasonably ascribed only to low-level erosion during epochs of Glacial emergence. The movement of subsidence by which the present relation of land and sea was brought about must have been, at its close at least, relatively rapid; for here, as on Tutuila, the small notches commonly seen a little above present sea level in the slanting face of the great plunging cliffs seem to have, in their wall height and bench breadth, the ratio of sine and cosine of the angle at which the half-submerged cliff faces slant. The slight emergence of these benches may be due either to a small elevation of the island or to a small lowering of ocean level, or possibly in part to a reduction of tidal range in the lagoon after its enclosure by the upgrowth of the great barrier reef, as Johnson has suggested for the small emergence of the east coast of Florida, back of

the lagoon-enclosing sand reefs which occur there. In view of the frequent occurrence of similar small emergences elsewhere, a lowering of ocean level is perhaps, as Daly has urged (1920a), the most probable of these causes; but the apparent absence of similar small emergences on many coasts of the world makes this cause uncertain.

The depth of the enclosed lagoon, usually from 20 to 40 fathoms, is by no means so great as the estimated rock-bottom depth of the visibly embayed valleys or of the sub-lagoon rock platform. Hence the reef must have grown up and the lagoon floor must have been aggraded scores or hundreds of feet during and after the subsidence of the island. Nevertheless, the lagoon has an ordinary depth, and lagoon floor aggradation must therefore be looked upon as an active process. The effects of Glacial changes of ocean level and temperature are no more discoverable here than at Tutuila and Tahiti.

The cliffs of Tutuila and of Tahiti appear to have been cut when the cones of those relatively young volcanic islands were in an early stage of active dissection. Similarly, as I have elsewhere explained in some detail (1918e), the cliffs of New Caledonia appear to have been cut when an unsymmetrical warping of the island, which depressed and embayed the southwest coast, raised the northeast coast which thereupon came to be fronted by a young coastal plain of sea-floor sediments. A defending barrier reef is supposed then to have grown up off the embayed southwest coast, which was therefore not cliffed; but no reefs could grow on the unconsolidated sediments of the imagined northeast coastal plain, which was therefore attacked and cliffed. The sequence of events here inferred is illustrated in Figure 117, the fuller explanation of which is given in the above-cited article. The explanation there presented is, to be sure, somewhat complicated and extremely hypothetical; but I have not been able to account for the existing features of the island in any simpler or better certified fashion. In any case, it seems more reasonable to propose even a hypothetical scheme for certain observed features of island form than to neglect not only such a scheme but also the features that call for it.

The Emerged Cliffs of Madras and the Plunging Cliffs of New Caledonia

An instructive parallel may be drawn between the now partly submerged cliffs of New Caledonia and the now wholly emerged cliffs of the Madras coast of India, described in an earlier section on reefless continental coasts. A no less instructive contrast may be drawn between the present reef-fronted coast of the one and the reefless coast of the other. As to the parallel, both coasts lie in the coral seas, yet both have been strongly cliffed during a reef-free period probably introduced by upheaval, when a coastal plain of sea-floor sediments was laid bare. As to the contrast, New Caledonia has suffered submergence after its cliffs were cut and has consequently become reef-fronted; but the Madras coast has

suffered a second uplift, revealing a second coastal plain, and therefore remains reef-free. The present reefless condition of the Madras coast may therefore be taken to represent, as I have pointed out in an earlier article (1918c, p. 545), the former reef-free condition of both these coasts, when the abrasion that eventually cut their great cliffs was just beginning.

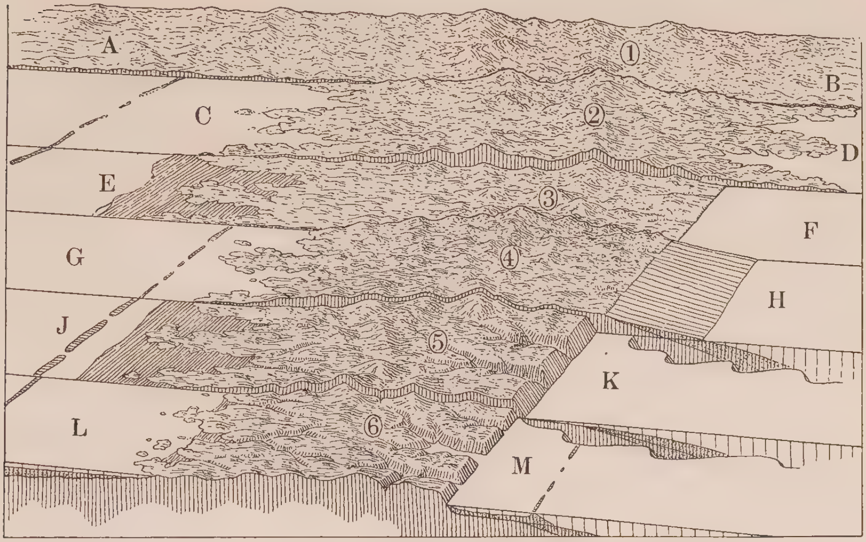


FIG. 117—Block diagrams, illustrating physiographic development of New Caledonia.

SUMMARY

The three islands described in this chapter are of importance as representing a stage of reef development to which attention has seldom been given; namely, the plunging-cliff stage intermediate between an early reef-free and cliffed stage, best represented by Réunion, and a later, reef-protected and drowned-cliff stage, thought to be represented by many typical barrier-reef islands. The early stage is closed by the subsidence which introduces the plunging-cliff stage, and the plunging-cliff stage is closed by the continued subsidence which drowns the cliffs in the later stage. The verity of the early stage of this explanatory scheme would be better certified if the spur-end slopes of Tutuila, which I have interpreted as plunging cliffs, had been so interpreted by the several recent students of that island. But they did not give any special attention to the spur-end slopes in which the vertical walls over the slightly emerged benches have been cut; hence my interpretation may, perhaps, stand for the present. The verity of the scheme would again be better certified if the occurrence of the cliffs of the northeast coast of New Caledonia did not depend on my own observations alone and if their explanation did not depend on an interpretation that is avowedly highly

hypothetical. On the other hand, the verity of the scheme, in which subsidence is an essential element, may be said to gain some support from the consistence of the explanation that it provides for the three widely separated islands, as well as from the instructive parallel and contrast that it suggests between the northeast coast of New Caledonia and the Madras coast of India. Its further test must be left for future observers.

The rarity of cliffed islands in the coral seas bears pointedly on the suggestion that barrier reefs have not been built up on subsiding foundations chiefly by corals, as Darwin proposed, but have been built up on stationary foundations, chiefly by nullipores, which can live in deep and cold water, and that corals have only added a shallow crown to the great nullipore structures. If this were true, the originally conical islands still-standing and unprotected while the nullipores were building up their deep banks, would today have well cliffed, non-embayed shores; but as a matter of fact nearly all barrier-reef islands have well embayed, non-cliffed shores, as will be fully shown in Chapter XIII. Hence the supposition that nullipores can build up heavy reefs from deep water around still-standing islands seems to remain only an abstract possibility; it is surely not a verified actuality. And even the abstract possibility is wide open to question, for, although some nullipores can live in cold waters at moderate depths such as 50 fathoms, it is extremely doubtful whether any can live at great depths where sunlight does not penetrate.

CHAPTER XII

EMBAYED, FRINGING-REEF ISLANDS WITHOUT PLUNGING CLIFFS OR BARRIER REEFS

Outline of Inquiry

Embayed and reefless islands standing on submarine shelves near continental coasts have been described in an earlier chapter. The few embayed islands, more or less reef-fringed, here presented are not parts of continents. They differ from the islands of the preceding chapter in being without barrier reefs and also in not showing plunging spur-end cliffs, which are therefore supposed to be, in so far as they exist, completely submerged. They resemble the islands of the following chapter in not showing plunging cliffs but differ from them in not having barrier reefs, probably because of rapid submergence. The present chapter is therefore directed to ascertaining if the position occupied by the islands here described represents a second intermediate stage in a sequence of developmental changes.

Fringing Reefs Have the Same Geographical Limits as Barrier and Atoll Reefs

It is a striking fact that thin fringing reefs have the same geographical limits, evidently determined by surface temperatures, as thick barrier and atoll reefs. This would seem to mean that the temperature of the water in which thick barrier and atoll reefs began their growth was essentially the same as that in which fringing reefs now live. If this be true it follows that, however thick barrier and atoll reefs may have grown, they began and carried on their growth in shallow water; in other words, that their upgrowth has accompanied the subsidence of their originally shallow foundations, as Darwin assumed.

A further consequence of this line of reasoning is that the greater part of deep barrier and atoll reefs cannot have been built up, as suggested on the previous page, by cold-resisting nullipores from deep foundations on stationary islands; for in that case fringing nullipore reefs should occur in surface waters of the cooler seas that are as cold as the waters are at the depth of barrier and atoll reef foundations in the coral seas; but no such cooler-sea fringing reefs are known.

Mt. Trafalgar and the Coast of Northeastern New Guinea

The first example to be presented is Mt. Trafalgar, HO 2961, 2964 (Fig. 118), not an island but a volcanic promontory on the north coast of New Guinea near its eastern end. The mountain is 8 or 10 miles in radius, 5584 feet in height, and has nearly 40 embayments up to 2 miles in

length where its northeastern quadrant advances into the sea. The embayed valleys and the spurs between them radiate systematically from the high central summit of the volcanic cone, showing that they result from the work of well developed consequent streams. Moresby briefly described the spurs as descending "to the sea in open grassy and wooded slopes" (1873–74): hence they are probably not cliffed. Some of the spur ends now bear fringing reefs, but others are charted as reefless. No shallow bank fronts the coast; depths of 50 and 60 fathoms and no bottom are charted a few miles offshore. The more continuous initial shore line of the promontory may, before recent submergence, have been reefless and cliffed during the erosion of its valleys, as the amount of detritus outwashed from so large a mountain on so rainy a coast must have discouraged the growth of corals; yet flourishing reefs must have been then forming in the Louisiade Archipelago not far away to the east.

Fig. 118—Mt. Trafalgar and Nelson Peninsula, north coast of New Guinea; HO 2961.

If reefless for a time long enough for the erosion of the now-embayed valleys, the promontory must, as above noted, have been cliffed at the same time; and, if the absence of spur-end cliffs on the chart means their absence on the actual coast, the post-erosional submergence must have been greater than the cliff height and must also have been too rapid to have permitted barrier reef upgrowth. Whether the amounts of pre-submergence erosion and of post-erosion submergence as indicated by the dimensions of the embayed valleys are greater than can be accounted for under the conditions offered by Glacial changes of ocean level, cannot be safely determined from the scanty data at hand. Yet if the Banks-Helena contrast be recalled, the embayed coast of Mt. Trafalgar, which strikingly resembles that of Banks Peninsula except in the absence of spur-end cliffs, will have to be explained by subsidence after the erosion of its valleys; but a somewhat different explanation is offered below.

Farther southeast, HO 2950, 2961 (Fig. 119), the coastal mountains

of the narrowing Stirling range, composed chiefly of ancient schists, disappear by dipping below sea level and thus gaining a well embayed, non-cliffed shore line, mostly without charted reefs; but there is no reason to think that the belt of deformed rocks ends here: it undoubtedly goes on farther and reappears in the Louisiade islands. The dimensions of the embayments at the end of the visible range are clearly much greater than can be accounted for by low-level erosion during the Glacial epochs. Depths of 60 and 120 fathoms and no bottom are charted near the shore. Moresby described parts of this coast as "washed by a grand, clear, reefless

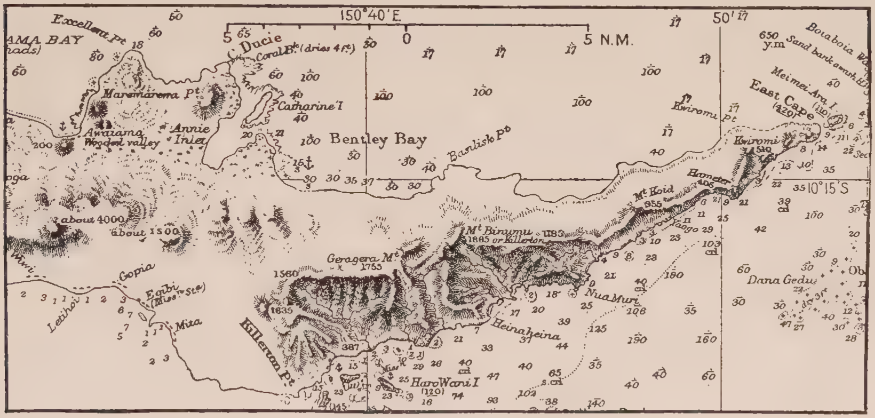


FIG. 119—The reefless northeast point of New Guinea; HO 2950.

sea; a ship might literally sail with her sides rubbing against the coral wall [a narrow fringing reef] which binds the shore, and find good anchorage in any of the bays where a breach [in the reef] is seen" (1873–74, p. 28). The absence of a barrier reef here is in striking contrast with the strong development of such a reef along the south coast, as is told in Chapter XIII.

Maitland has briefly announced the occurrence of well preserved fringing-reef terraces resting unconformably on the degraded rocks of the mountain flanks along this coast at various altitudes up to 2000 feet (1892, p. 20; 1905, p. 41). An active double movement of the deformed and eroded mountain range must therefore be inferred: first a great subsidence and then a less great upheaval. The elevated fringing-reef terraces must have been formed during pauses in one movement or the other, except that the highest reef may be taken to mark a pause between subsidence and upheaval. It is therefore possible that this coast, and perhaps the Mt. Trafalgar promontory as well, should not be regarded as having been embayed by a recent and rapid subsidence of moderate measure but as preserving moderate embayments because a great submergence of short duration has not been entirely counteracted by an emergence of smaller measure. If such be the case, the failure of barrier-reef growth along the coast is natural enough.

The absence of a barrier reef along the northern coast of eastern New Guinea, as just described, is repeated around the irregular and occasionally fringed shores of the D'Entrecasteaux Islands, BA 938, 15 to 30 miles distant to the north; but the absence of shallow circuminsular banks is not assured there; one of the islands, Normanby, is fronted by an exceptional barrier reef 20 miles long, 2 miles off its southeastern side; a number of reef patches and shoals lie farther seaward.

The Philippines and Other Islands

Many of the Philippine Islands have embayed shore lines with fringing reefs on their headlands, below which the submarine slope descends either to a shoal or to great ocean depths. They may therefore be taken as affording examples of fringing reefs of a new generation, formed on coasts that have been rapidly submerged to their present attitude, and as therefore illustrating a principle regarding reef formation clearly announced by Darwin but generally overlooked by later writers, as has been pointed out in Chapter II.

Mindanao, the easternmost island, may be here cited. Part of its eastern coast, CS 4626, has well developed embayments, between which the headlands have narrow or no fringing reefs; the submarine slope descends to deep water. Farther north, CS 4627, the embayments are stronger still; their heads are delta-filled, and the intervening points have fringing reefs half a mile or more wide; they descend to a submarine shoal 1 or 2 miles wide and from 25 to 40 fathoms deep. These features continue on CS 4628, but near its northern margin the shoal broadens to 5 or 10 miles, with depths of 40 or 50 fathoms and some indications of a shallower outer margin.

North of Mindanao is the smaller island of Dinagat, CS 4638, 10 by 25 miles, 2000 or 3000 feet high, with a steep coast descending to a strongly indented shore line where narrow and discontinuous fringing reefs are shown on the headlands; a shoal about 30 fathoms deep extends 30 miles to the east of this island. Farther northwest the eroded and embayed east coast of Samar bears unconformable fringing reefs on at least some of its headlands and is, for a fraction of its length, fronted by a bank 5 miles wide and 25 or 30 fathoms deep, from part of the outer margin of which rises a well defined barrier reef about 3 miles long, known as Hilaban Island, for which a profile is given by Schenck (1922, p. 249). The peninsular extremity of the large island of Luzon, CS 4222, is reached with Catanduanes Island near by on the east. The shore lines are much embayed, with a variable development of fringing reefs up to 1 or 2 miles in width. A shoal, 30 or 40 fathoms deep and 10 or 20 miles wide, surrounds the island and extends to the north of it; but Lagonoy Gulf, next southwest, has no fringing reefs on its shores and is 500 fathoms deep.

Examples of this kind might be greatly multiplied. They all go to con-

firm the instability of the Philippine Archipelago; but detailed field work will be needed to supplement a study of the charts before the meaning of the variations of coastal form, of reef development and of submarine slopes can be safely asserted. In the meantime it is held to be probable that the shoals above noted and others like them represent submerged reefs and lagoon plains, formed during an earlier period of subsidence. No other means of producing such circuminsular shoals seems so competent as this one. Moreover, this cause is well certified as competent in the case of Palawan, the southwesternmost member of the group; it has already been cited in Chapter II and will be described more fully in Chapter XVII, where a number of other shoal-surrounded islands having fringing reefs on embayed, non-cliffed shores will also be treated. Some of the islands bear unconformable fringing-reef terraces at moderate altitudes. In such cases, the highest terrace presumably marks the level of greatest submergence, and the fringing reefs at the present shore line should be interpreted as formed during a pause in a following emergence; the emergence being less than the submergence because the shore lines are still embayed. The highest of such reefs would therefore exemplify Darwin's special explanation for fringing reefs following submergence; the others may have been formed during earlier pauses in the submergence or during later pauses in the emergence.

Ndeni, the largest member of the Santa Cruz group, HO 1985, measures 23 by 10 miles and has a height of over 1800 feet; it is well dissected and moderately embayed but has no charted reefs, either fringing or barrier. It is very likely surrounded by a submerged reef, but no soundings are given by which this likelihood may be tested. If a submerged reef occur there, its submergence must be of so recent a date that no fringing reefs of a new generation have yet been formed on the present shore line. The same may be said of Banta, near Sumbawa, HO 3006, 4 miles in diameter, well embayed but not reef-encircled. The Horne Islands, north of Fiji, probably resemble Ndeni in this respect; they will be described in Chapter XVII in connection with the group of drowned atolls, north of Fiji, for which I have proposed the name "Darwin Hermatopelago." One of the four volcanic islands between northern Madagascar and the African coast is Johanna, BA 563, a slender, T-shaped island, 19 by 2 miles, 5250 feet high, with a few fringing reefs but no barrier reef, although its outline suggests submergence after advanced erosion. As no soundings are charted there, the existence of a drowned barrier reef may be suspected but for the present is not confirmed.

Summary

The small number of islands that qualify for mention in this chapter hardly warrant a generalization regarding the stage represented by them in the general scheme of island and reef development here followed. It

may, however, be stated tentatively that, as far as the few volcanic islands here cited are to be trusted, they seem to have subsided after an earlier stage of dissection and presumable cliffing, and as a result they have embayed coasts, but that the subsidence has been too rapid for the accompanying upgrowth of barrier reefs from any early established fringing reefs. If, during the earlier stage of dissection, any cliffs were cut around the island shores, they appear to have been completely submerged.

CHAPTER XIII

EMBAYED, NON-CLIFFED ISLANDS WITH BARRIER REEFS

Outline of Inquiry

A long and important chapter is now to be entered upon in order to determine whether the typical barrier-reef islands of the coral seas truly exemplify a mature stage in the theoretical history of subsiding volcanic islands, as set forth in Chapter X. In other words in order to learn whether barrier-reef islands have been, except in their earliest youth, persistently protected from abrasion by upgrowing reefs during slow, long continued, presumably intermittent subsidence, according to Darwin's theory, or whether they have been, during a late phase of long continued stability, temporarily deprived of reef protection and attacked by low-level abrasion, according to the Glacial-control theory. It is desired also to determine, in case the inquiry results in the adoption of the first alternative, whether any consequences of Glacial changes in ocean level can be detected. Let it be understood while this chapter is read that, although a depth limit of about 20 fathoms for coral growth was an inherent postulate of Darwin's subsidence theory, the barrier reefs here treated are believed to have grown up during the subsidence of their foundations not because that postulate demands subsidence for the production of barrier and atoll reefs but because wholly independent evidence, quite unknown to Darwin, shows that the demanded subsidence took place.

Barrier-Reef Islands of the Society Group

General Account

No other archipelago in the Pacific coral seas includes so systematic a sequence of island forms as those of the Society group. The sequence begins with a young and reefless volcanic island on the east and ends in several small atolls on the northwest. The young cone of Mehetia, 65 miles east of Tahiti, has been described, in accordance with Agassiz' account, in Chapter X as moderately cliffed where it is not defended by narrow and discontinuous fringing reefs. Tahiti, a much larger, submaturely dissected island, has been described in Chapter XI; it exemplifies to perfection the expectable features of a cone that was strongly cliffed in its reefless youth, has since then suffered subsidence and embayment, and has consequently gained reef protection, although it has not yet subsided so far as completely to submerge its early-cut cliffs. Moorea or Eimeo, nine miles northwest of Tahiti, is farther advanced in the sequence, for it shows cliffed spur ends only on a small part of its shore circuit; elsewhere the spurs slant down in tapering fashion into its narrow,

barrier-reef lagoon. Huaheine, 75 miles northwest of Moorea, together with Raiatea and Tahaa, 18 or 20 miles farther west, are of typical, maturely dissected form with sloping, non-cliffed spurs, embayed shore lines, and well developed barrier reefs; Tubuai Manu, to the southwest, also known as Maiao, appears to be in the same mature stage but has not been as yet well charted. Borabora, 10 miles northwest of Tahaa, shows in the denuded peak of its central stock and in its worn-down spurs a more advanced stage of dissection and in its broad embayments a more advanced stage of submergence than the preceding members; it has a maturely broadened barrier reef. Maupiti, a much smaller and lower island 24 miles northwest of Borabora, has a barrier reef so broad and a lagoon so narrow that it might almost be described as an unusually wide fringing reef; the island survives only in the non-embayed peak of a central stock, such as Borabora would show if it were 1000 feet more submerged. Beyond Maupiti to the north and west are four small atolls; and a fifth, Tetiaroa, lies farther east, north of Tahiti.

Volcanic action would thus appear to have begun in the northwest and to have advanced to the southeast and east, as is also the case in the long Hawaiian chain; but there the islands and their reefs show forms characteristic of the Pacific marginal belt, while here they show forms characteristic of the coral seas. That the islands thus successively formed in the Society group have subsided—the first-formed and oldest ones in the west, the most, the last-formed and youngest ones in the east, the least—seems to me indisputable. That abrasion characterized the early stage of each island is indicated by the initiation of abrasion in the low cliffs of Mehetia, the youngest and easternmost; by its more advanced progress in the strong truncation of the cliffed spurs, now partly submerged, in the larger and further developed island of Tahiti; and by the survival of a few cliffed spur ends on the more maturely dissected island of Moorea, although most of its shore is not cliffed. The absence of visible spur-end cliffs on the other islands is a most natural consequence of the greater subsidence apparently suffered by them. Indeed, in view of the prevalence of abraded shore cliffs around young volcanic islands, as shown in Chapter XI, it would seem almost as unreasonable to doubt the occurrence of completely submerged and hence invisible cliffs of abrasion on the submarine flanks of Huaheine, Raiatea, Tahaa, Borabora, and Maupiti, as to doubt the volcanic origin of those islands. And, on a similar line of reasoning, it would be about as unreasonable to deny that the wholly submerged foundations of the northwestern atolls are well dissected volcanic islands, cliffed around their original shore line, as to deny that those atolls have any volcanic foundation whatever. The systematic coherence of the explanation offered by Darwin's theory for all these islands commends it no less than its capacity of bringing the whole series of unlike islands into an orderly sequence.

The aid here given by the "clue of theory" in reaching a larger under-

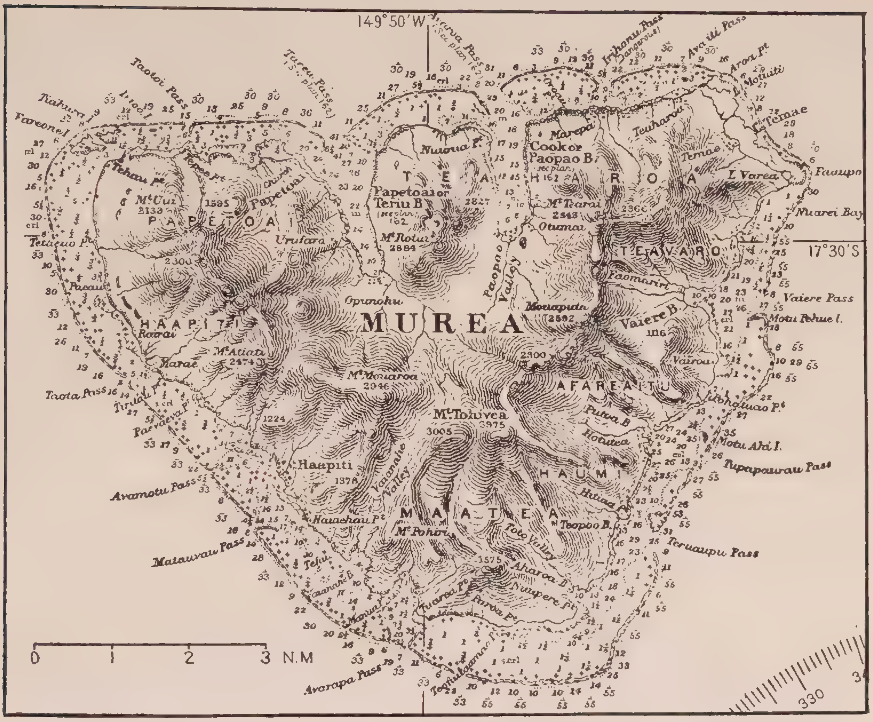


FIG. 120—Moorea, Society Islands; HO 2065.

standing of many dissimilar facts is truly wonderful. Just as one may, on each island, place all the elements that make it up in their proper genetic relations to each other, so one may place each island in its proper genetic relation to the group as a whole. Surprisingly enough, when the islands are thus placed, their genetic sequence agrees closely with their geographical sequence. On the other hand, it has been impossible to find on the islands of this group a single fact, apart from the moderate and fairly accordant depth of their barrier-reef lagoons, that gives support to the Glacial-control theory. But inasmuch as the wholly independent evidence for subsidence demands that the lagoons shall have been aggraded to their observed depth while subsidence was in more or less intermittent progress—with any modifications of their depth that have been recently entailed by Glacial changes of ocean level—this very insufficient support for that theory here loses the small value it may have elsewhere.

My visit of a month, September 24 to October 22, 1914, to several islands of this group was made on the return voyage from Australia. On arriving at Papeete, Tahiti, kind assistance was given me by His Excellency the Governor, M. William Fawtier, and by various residents with whom I made acquaintance. Transportation from island to island was afforded by the launches of the Compagnie Navale de l'Océanie, on

which I visited Moorea, Huaheine, Raiatea, and Borabora; local sail-boats carried me around the lagoons of Huaheine, Raiatea and its neighbor Tahaa, and Borabora; and I ran around a good part of the lowland border of Tahiti in an automobile. I am much indebted to Prof. Harrison W. Smith, formerly of Boston, later resident on Tahiti, for several excellent photographs here reproduced. As Mehetia and Tahiti have been de-

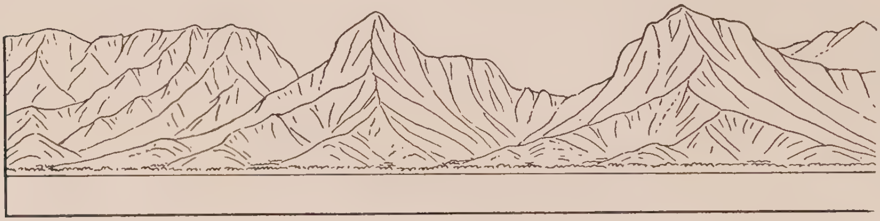


FIG. 121—Southwest

scribed in earlier chapters, the present account of the Society group will begin with Moorea.

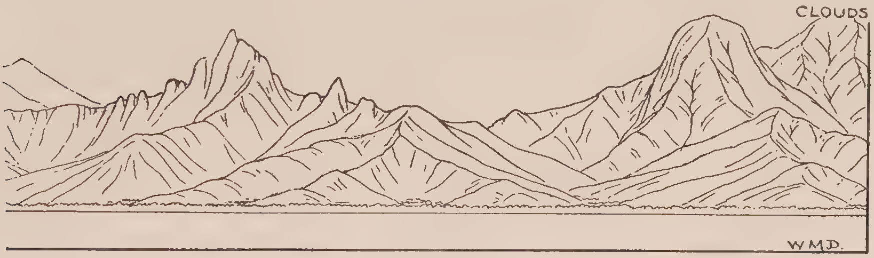
Moorea and Its Surviving Cliffs

Moorea or Eimeo, HO 2065 (Fig. 120), 9 miles northwest of Tahiti and 3975 feet high, has in plan the outline of an equilateral triangle, 7 miles on a side, one angle of which is turned to the south, so that the opposite side faces to the north. The island seems to be the greatly eroded residual of a single volcano, which may have originally had the form of a dome, as the heavy lava beds in certain lateral ridges show only a gentle outward inclination. No trace of the original surface now remains. The serrated ridges reach heights of 2000 or 3000 feet over the southwestern and southeastern sides of the triangle and, uniting southward in a V, culminate in several fine peaks nearly 4000 feet in height at the V angle; one of these peaks is shown in the frontispiece. The southwestern ridges (Fig. 121), of which a fine view was had from the steamer on the approach to Tahiti, are of especially picturesque form. The northern side is cut down in two deep and broad valleys, separated by a ridge that terminates in a bold knob over the shore. The interior between and beyond these valley heads is a hilly lowland. If a large caldera originally occupied the island center, the caldera floor as well as its rim has suffered great degradation in reduction to present island form; the two broad northern valleys probably represent the course of rival outlet streams. Thus, while Tahiti is loftiest at its center, Moorea is lowest there.

Discharge of Eroded Detritus from Moorea

The erosion suffered by Moorea in its reduction to residual peaks and spurs should be carefully estimated by those who study the origin of its encircling barrier reef; for the magnitude of the erosion offers the best

means now available for making choice between the only two coral-reef theories that are there and today worthy of consideration. The choice between the two theories turns primarily on the measure and date of any subsidence which the island has experienced and in association with which its encircling reef has grown up. If the island had remained stationary



coast of Moorea.

since its eruptive construction, the active discharge of stream-washed detritus from the initial slopes of its youth would soon have smothered any incipient fringing reefs on its shores and the island would then have long remained reefless and exposed, like Tahiti, to abrasion. Its margin should therefore have been cut back in cliffs, and the cliffs should still be visible today. But, with the exception of four pronounced spur-end cliffs on the western half of the northern shore, of which further account is given below, the mountain spurs slant down to the lagoon and dip gradually under its waters. Whatever cliffs were, like those of Tahiti, cut around most of the island circuit in its early youth are no longer visible; hence they must have been drowned by subsidence, and the island has not remained stationary since its eruptive construction. How much subsidence has been necessary to drown the early-cut cliffs remains to be estimated. The estimate should be made in view of the vast amount of erosion suffered by the island and hence in view of the vast volume of detritus that has been removed in its reduction to its present form.

Even if a good-sized caldera originally occupied the island center, the erosion necessary to reduce the island from the initial to the present maturely dissected and degraded form would provide detritus sufficient to fill the present lagoon 50 or 100 times at least; the lagoon breadth being taken as half a mile and its depth as 20 fathoms. In order to dispose of so much detritus, it seems necessary to suppose that most of it was discharged before persistent reef growth was initiated; and hence that island-rimming cliffs were cut back during that discharge. If the young island were stationary during a long period of detrital discharge, high cliffs would have been cut around its undefended shores; and a great subsidence would have been necessary afterwards to drown such cliffs. Let it therefore be supposed that slow subsidence was in progress during the early discharge of detritus: a subsidence so slow that cliff-base beaches on

which no reefs could grow were continuously maintained around the shore line. The resulting cliffs would then be of less height than those cut in the same period of time on a stationary island; and hence a smaller measure of later and more rapid subsidence accompanied by reef upgrowth would suffice to drown them. The moderate offset of the present barrier reef suggests that this later subsidence has not been of very great measure. But if the earlier slow subsidence and the later faster subsidence are added together, they must make a large total subsidence, which is more reasonably estimated to be one or two thousands rather than only a few hundreds of feet; and this very emphatically favors Darwin's theory.

The persistence of several spur-end cliffs on the northern coast remains to be accounted for. It is noteworthy that the cliffs rise to the west of the two large valley embayments which there indent the shore line; also that the valleys of the two large embayments drain a great central area of the island and hence must have discharged a major part of the detritus that was eroded during the progress of deep island dissection. It is therefore permissible to suppose that, even after the initiation of the more rapid subsidence by which the smaller valleys were embayed, and also after reef upgrowth was begun and cliff cutting was stopped around most of the island circuit, the two northern valleys were kept delta-filled; further, that, impelled by the trade wind, a shore current carried detritus westward from the delta fronts and locally prevented reef growth and permitted cliff cutting beyond the deltas for a considerable period. The longer continued cutting of cliffs there would make them higher than elsewhere; hence their upper faces should still be visible even after an accelerated subsidence had embayed the large northern valleys and permitted reefs to grow up across their mouths and farther west, thus completing the circuit of the barrier. The explanation thus offered for these cliffs is, as in the case of the cliffs along the northeastern coast of New Caledonia, so hypothetical that it is beyond the reach of complete confirmation today; but it seems to me to be at least a step toward a fuller statement of Moorea's history, just as the recognition of the cliffs which it explains is a step toward the island's fuller description than has heretofore been made.

The Bays and Reef of Moorea

The two large-valley, northward-opening bays of Moorea are now about a mile and a half in length and from a third to half a mile in breadth. Their estimated rock-bottom depth at the mouth is at least 600 or 800 feet; but they have soundings of only 15 or 20 fathoms; the passes in front of them are of similar depth. The many other bays of the island are of much smaller measure.

The barrier reef of Moorea follows the outline of the shore with unusual fidelity at a distance of half or three-quarters of a mile. It is interrupted by 11 passes, all opposite valleys; but there are many valleys

opposite which no passes occur. If the slopes of the non-cliffed island spurs be continued under the lagoon, they would pass below the reef at depths of from 500 to 800 feet; but, if the reef has an inward inclination, its base may lie at a much greater depth. As the above argument regarding abrasion and subsidence also suggests a considerable depth for the reef base, its upward and inward growth seems plausible. The lagoon has maximum depths of 20 or 25 fathoms; but it is generally shal-

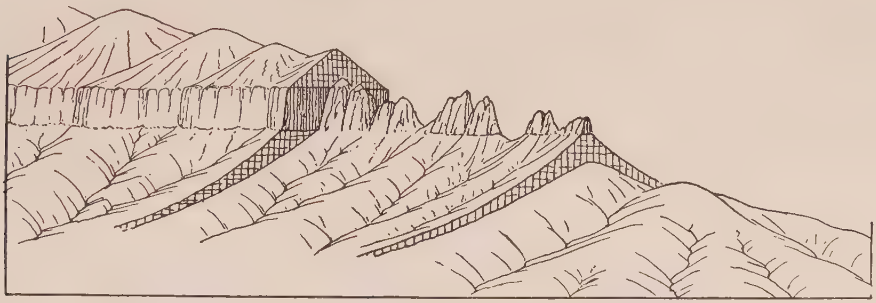


FIG. 122—Diagram, showing evolution of spur forms on Moorea.

lower, and around the northeast corner of the island it is almost filled. Crossland (1927) reports that the reef of Moorea is slightly elevated on its northeast curve and hence infers a gentle tilting of the island. He notes also that the Moorea barrier, like that of Tahiti, is wasting and suggests that for this island as well as for its larger neighbor the age of corals is past. But here, as there, the wasting of the reefs would seem to be due rather to the encroachment of volcanic detritus across the shallow and narrow lagoon than to any failure of coral growth in itself; hence here, as there, this cause of weakened growth would seem to be effective decidedly before the reef-enclosed lagoon is filled with detritus as pictured in Figure 53 (Chapter VI).

The Sculpture of Moorea

The problem of the Moorea barrier reef becomes the problem of Moorea itself or, more particularly, the problem of the erosion suffered by the island; and to the more visible effects of that erosion we may now return. The grandly carved mountains have excited the admiration of all visitors. They have been described by Ellis (1833, Vol. 1, p. 29), Stewart (1831, Vol. 2, p. 53), the "Earl and the Doctor" (1872, p. 48), Agassiz (1903a, p. 156), and many others; but none of these observers has considered the relation of island sculpture and reef growth. Yet it is the manifest discordance between interior structure and surface form, as well as the equally manifest accordance between surface form and long-acting erosional processes, that demonstrates the enormous change suffered by Moorea since it was handed over by volcanic constructional forces to subaerial destructive processes. And it is the manifest necessity of disposing

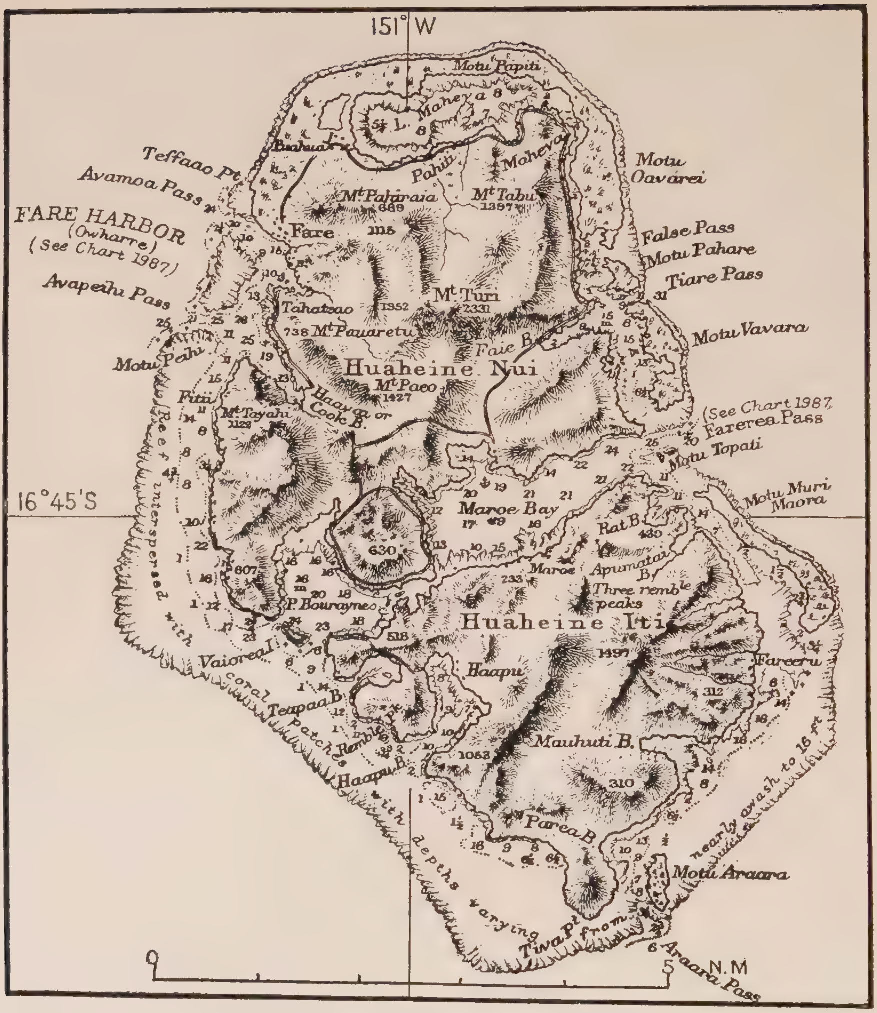


FIG. 123—Huaheine, Society Islands; HO 2023.

of the detritus that was discharged during this enormous change that demands the consideration of the relation between island sculpture and reef growth.

The regular progress of the destructional processes is well illustrated in certain castellated or pinnacled ridges of middle height (Fig. 122), which are capped by a heavy series of resistant lava flows overlain and underlain by weaker beds. If one of these ridges is followed inward, the pinnacles become enlarged into castles, and farther on the castles become united in huge, pyramid-topped fortresses. If the ridge is followed outward, the pinnacles, dwindling away, are replaced by lowered, rounded crests of gradually decreasing height. It is, however, not so much

through the beauty of its mountain sculpture that Moorea is related to the coral reef problem as in the disposal of the detritus provided by the sculpture. No theory which takes adequate account of this element can dispense with the factors of island subsidence and reef upgrowth which inhere in Darwin's theory, for the detritus cannot have been disposed of without the aid of subsidence. It is surely a great commendation for the

FIG. 124—Central bay of Huaheine, looking north to Mt. Turi.

old theory that it so competently accommodates the important element of the disposal of detritus, to which no attention was paid when the theory was invented. Moorea, thus understood, forms a fitting neighbor to Tahiti.

HUAHEINE AND ITS DISSECTED CALDERA

Huaheine, HO 2023 (Fig. 123), 8 miles north-south by 4 miles across and 2391 feet high, lies 75 miles northwest of Moorea. It seems to represent a volcano of oval outline, as all of its lava-bed outcrops slant away from a single center. The central area appears to have been occupied by a large caldera, because its low hills are enclosed by a rim of much higher marginal mounts; but both the rim and the floor of the caldera have been deeply dissected since volcanic activity ceased, and the well carved mass has been rather strongly submerged since it was dissected. The original caldera rim is now cut down in notches by a number of consequent streams, between which a similar number of residual mounts rise from the shore in triangular slopes; they might be called buttresses, except that they do not lean against anything but only overlook the lower central area. They are most regularly developed in the southern half of the island, where they are maintained at a vertex height of 1000 feet or more by heavy, outward-slanting lava beds, 50 or 100 feet thick, which seem to overlie a central body of weaker volcanic deposits.

The highest buttress mount, Turi, 2391 feet in altitude, rises inward from the northern curve of the island and dominates the hills of the cen-

tral depression; it is drawn as seen from the south in Figure 124 and as seen from the west in Figure 125. The consequent exterior slope of all the buttresses is inclined outward at a moderate angle but little less than the dip of the maintaining beds; the obsequent or inward slope is much more abrupt next under the slanting cap layers but declines more gradually below to the rolling hills of the weaker central beds. Two good-sized knobs

FIG. 125—Delta at head of a drowned valley embayment below Mt. Turi, west coast of Huaheine.

at the northeastern curve of the island and a small ledge at its southern extremity rise outside of the buttress slopes; they may represent worn-down survivals of subordinate and peripheral centers of eruption.

The two longest consequent valleys, one opening on the mid-east coast, the other on the mid-west, have many insequent branches among the worn-down hills of the central caldera floor; outcrops are rarely seen there as the hill slopes are usually well graded. Valleys of intermediate length are seen in the northwestern part of the island, where they are rather broadly opened between the buttress mounts and well expanded inland by apparently subsequent branches that seem to be guided by weak beds underlying the buttress-making harder lavas, as shown in Figure 125. Several shorter consequent valleys in the southern half of the island are narrow and fairly steep-sided where they cut through the slanting lava caps of the buttresses, but they also widen upstream by the development of short subsequent branches on the weak beds under the lava caps.

The Embayments of Huaheine

The sea now enters all the valleys of Huaheine in bays or coves up to two miles in length. A bay heading in one of the broad northwestern

valleys is shown in Figure 24. The coast nowhere exhibits any sign of plunging cliffs, such as those which characterize the greater part of the circuit of Tahiti and a short part of the north coast of Moorea; but the lagoon waves have cut little bluffs and narrow platforms at present sea level on some of the spur ends.

It is not possible to agree here with Agassiz, who, tacitly postulating island stability and assuming the former action of marine erosion, stated that "Huaheine . . . shows perhaps as well as any of the other islands, the manner in which the wide platform of erosion has little by little been formed by the action of the sea" (1903a, pp. 136–137); nor can Huaheine be accepted in evidence of the "extensive submarine denudation," which Agassiz thought had produced "the great variety of submarine platforms . . . at the base of volcanic islands . . . throughout the Pacific, the depth of these platforms being fairly indicated by that of the lagoons enclosed by the encircling reefs" (1903a, pp. xviii–xix). The sea has, truly enough, encroached upon the flanks of Huaheine and entered all its valleys, as above noted; but the encroachment is the result of island submergence, not of marine abrasion. Moreover, the submergence must be ascribed not to the Postglacial rise of ocean level but to subsidence of the island for three reasons: First, because the larger embayments are too widely opened to be explained by the low-level erosion of a stationary island during the Glacial epochs; second, because the inferred rock-bottom depth of the larger embayments appears to be greater than the supposed lowering of the Glacial ocean; third, because, in spite of the removal of a great volume of eroded detritus—during the early discharge of which the island would have been kept free from defending reefs and would therefore have been cut back in shore cliffs—not even the tops of any such cliffs are now to be seen.

The Barrier Reef of Huaheine

The oval circuit of the barrier reef that surrounds Huaheine measures about 9 miles north-south and 6 miles across. It is interrupted by five passes, which are opposite certain valleys, including the two largest. Many of the smaller valleys have no reef passes in front of them. The enclosed lagoon is from half a mile to a mile in width; its soundings are from 10 to 20 or 25 fathoms; but it is often shallower, especially around a large northeastern arc of the reef circuit, where the broadened reef flat bears long, tree-covered sand islands. Indeed, back of these sand islands the lagoon around the northern curve of the island, where the dissected mounts of the caldera rim are highest, is replaced by a tree-covered plain, except that a middle part of the plain is occupied by a shallow fresh-water lake.

The week that I spent on Huaheine allowed me to make a trip of circumnavigation through the lagoon around the southwestern half of the island but outside of the reef around the northeastern half, and also to

enter many of its bays and valleys and ascend a few of its hills. It also afforded leisure for visits to parts of the reef off both the east and the west coast. A half-mile segment of the western reef bore 2000 or 3000 wave-thrown blocks of coral, from 2 to 5 feet in diameter; their pitted and ragged surface showed various stages of disintegration. I pointed with an interrogative gesture to a dozen or more volcanic cobbles, up to a foot in diameter, that lay on the reef; and my canoe boy answered at once by extending his arm to the main island as their source: they had probably been brought out for ballast, or some such use. Much of the reef crest here is narrow, with a ragged, rocky surface. The seaward slope is so gentle that the reflux of the surf surge laid the rocky surface bare for 30 or 40 feet; and through the steep concave face of the next-coming breaker, 8 or 10 feet in height, the mottled colors of abundant corals could be seen under water.

The inner side of the reef falls off by an abrupt face, from 2 to 5 feet in height, to a slope of coral sand strewn over with reef blocks on which small corals are growing. At time of storms, the strength of the sweeping surge and the volume of water and reef sand that is carried into the lagoon must be very great. It must be then that coral blocks are detached and swept over from the outer, growing face of the reef and left on the inner sand slope. Thus the lagoon is clearly being shoaled by deposition, not deepened by solution or by marine erosion. The barrier reef has grown up around the island during its subsidence; and the subsidence has been so great that the cliffs, which must surely have been cut around the island in its youth, have sunk out of sight. Glacial changes of ocean level have, of course, been experienced, but their effects cannot be detected. Huaheine thus forms a fitting fourth member of the sequence in which the earlier members are Mehetia, Tahiti, and Murea.

Raiatea and Tahaa and Their Figure-8 Barrier Reef

Raiatea

Raiatea—written Ulietea by Cook—HO 2023 (Fig. 126), 12 miles north-south by 7 across and 3389 feet high, lies 18 miles west of Huaheine. An excellent and well illustrated account of the island and its people has been written by Huguenin (1902), who spent five years there as director of schools. The mountainous mass probably represents two or more closely confluent volcanic cones and resembles Tahiti in rising to greatest height in a sharp central summit; but it is much more maturely dissected than that larger and younger island. The exceptional sharpness of the ridges over its mid-western and most abrupt side is shown in one of my sketches, Figure 127, in drawing which a careful attempt was made not to exaggerate the steepness of the slopes. Farther north and south on the west side, as well as all along the eastern side of the island the valleys are well opened and the spurs are of simpler, rounder form. They descend from the axial ridge in rather regular slopes of 10° or 15°; their shore ends are often

FIG. 126—Raiatea, Society Islands; HO 2023.

steepened in little bluffs of 30° or 40° slope with heights of 10 or 15 feet, as if they had been nipped off by lagoon waves; the bluffs are as a rule bordered by alluvial flats outwashed upon fringing reefs, so that any rock platforms that may front them are not visible. Several spurs, subdivided into spurlets, at the northern end of the island are truncated in steep bluffs, 50 feet or more in height, thus recalling the much larger

cliffed spur ends on the north coast of Murea. A small landslide of recent fall upon the alluvial flat below blocks the easternmost valley in this group of bluffed spurs.

The valleys of Raiatea are now conspicuously embayed (Fig. 129), and the embayments indicate a strong submergence, which for the same reasons as in the case of Huaheine must be ascribed to subsidence. During a two-day sail around the lagoon I noted on a chart of the island the approximate measure of shortening that each bay had suffered by delta growth, as shown in Figure 126. It is thus seen that the two longest

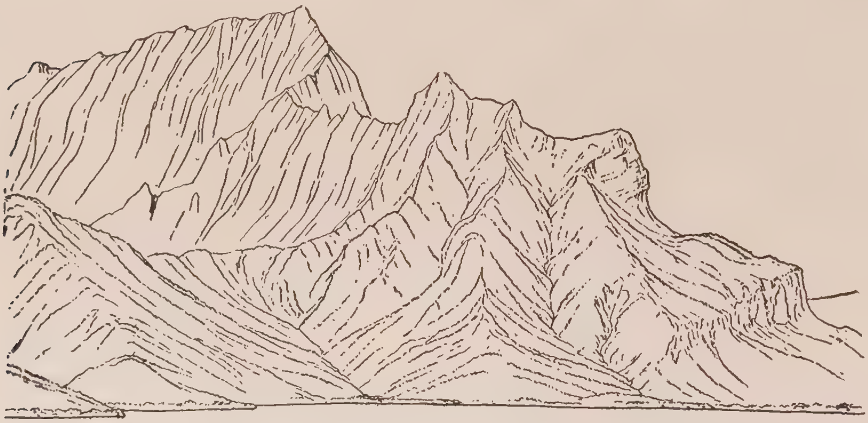


FIG. 127—Sketch of part of the deeply dissected volcanic mass of Raiatea, Society Islands. The embayment of the shore line, diminished by deltas, is not clearly shown because of foreshortening.

bays—Faaroa in the mid-east coast and Faatemu at the southern end of the island—would be longer still if their deltas were removed. It was presumably to Faaroa bay that Darwin referred as penetrating nearly to the heart of the island (1842, p. 49). Agassiz also was impressed by these "deep indentations or harbors, reaching into the valleys formed by the spurs running east and west from the main ridge" (1903a, p. 159), but he took no more account of them than Darwin did in determining changes of island level.

By reason of the regular descent of most of the island spurs, islands of volcanic rock are rarely seen in the lagoon. One, Haaio, a hilly knob half a mile long and about 200 feet high, lies near the south end of the island; two other small knobs of volcanic rock rise in the fringing reef flats, one near the mouth of each of the long bays above named. Like the spur ends, none of these islets are distinctly cliffed on their outer side. Other lagoon islands, all low and flat, seem to be mere reef patches. Hence I believe Agassiz was in error in stating that "the east shore of Raiatea is flanked with numerous volcanic islets" and that "off the west coast . . . numerous volcanic islets are enclosed within the shore fringing reef or rise from the deeper parts of the lagoon" (1903a, p. 161).

Fig. 129

Fig. 130

Fig. 129—An embayment in the east coast of Raiatea. (Photograph by W. M. Davis.)

Fig. 130—Surf and surge on the narrow barrier reef, eastern side of Raiatea. (Photograph by W. M. Davis.)

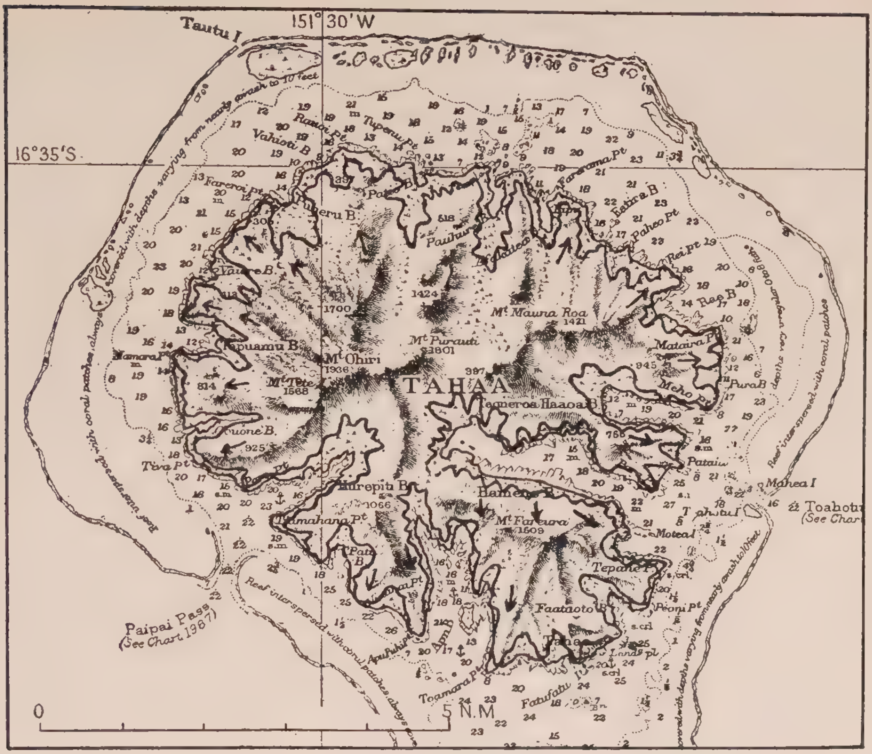


FIG. 128—Tahaa, Society Islands; HO 2023.

Tahaa

Tahaa, HO 2023 (Fig. 128), nearly circular in outline, six miles in diameter and 1936 feet high, lies two miles north of Raiatea. It is a single volcano, as is shown by the regular outward slope of lava and ash beds with a dip of about 10°, exposed in the sides of its many radial spurs, and shown by short arrows in the above figure. I made a close inspection of its embayed valleys on a one-day sail around the lagoon. A deeply excavated central depression, with discharge to the southeast, suggests that a crater or small caldera was originally breached on that side of the cone. The highest summits, 1936, 1801, and 1568 feet in altitude, occupy an eccentric position to the northwest of the central depression, over which they rise as the inward-scarped vertices of island sectors, which are separated by major consequent valleys and are incised on the outer slope by minor consequent valleys.

All the larger valleys are maturely opened and well embayed (Fig. 131). Four of the bays are over a mile in length, and the longest of these reaches the central depression, in which it gains a liberal breadth, as shown in Figure 132. However well this depression was foreshadowed by a crater, the floor of the crater must have been deeply eroded to give the depression

its present form. Ten other valley-mouth bays are of fair size. All of them were examined during my sail around the lagoon, and all were seen to be shortened by delta flats at their heads. If these good-sized bay-head flats and the smaller ones around the spur sides and ends were removed, about 200 additional coves of small size would be seen entering as many small ravines. Subsidence, as an aid in disposing of the great volume of detritus eroded from this island, seems indispensable. Following the principle of maximum embayment, outlined in an earlier chapter,

FIG. 131—Tahaa, as seen from a

the subsidence of Tahaa should measure a large half of its remaining height, or 1000 feet at least. This confirms the strong subsidence that is inferred from the estimated rock-bottom depth of the larger embayments, from the disappearance of much eroded detritus, and from the absence of plunging cliffs of early abrasion.

A number of the spur ends are slightly nipped off in low bluffs, 10 or 12 feet high, fronted by rock platforms 20 or 30 feet wide, evidently the recent work of the lagoon waves. By way of exception, six spurs on the southwestern side of the island terminate in bluffs from 30 to 50 feet high; no rock platforms were seen at their base. I am at a loss to account for these higher bluffs, as well as for the several similar bluffs at the north end of Raiatea; they were probably all cut before the islands had sunk to their present level, but why the cutting should have taken place on these little-exposed parts of the shores is by no means clear. Whatever adequate explanation may be later found for them, their present interest lies in the contrast they make to the little-nipped, tapering spurs around the remainder of the island circuits, from which the unimportance of abrasion, even by lagoon waves, in fashioning the present outline of the islands may be safely inferred. Yet it may also be believed that, at an early stage in their history, both these islands discharged so much detritus to their non-embayed shores that they were long reefless and strongly cliffed. The inferred cliffs of that date are now lost to sight as if by reason of their complete submergence. Only three islets of volcanic rock were seen in the lagoon around Tahaa; two of them lie near the bay that opens southward toward Raiatea; the third lies a mile farther east. The reason for the prevailing absence of such islands is here, as in Raiatea, the regular slope of the distal part of the spurs.

The Raiatea-Tahaa Barrier Reef

The barrier reef that encircles both Raiatea and Tahaa in its double or figure-8 loops is a fine example of its class. Its inner border slants under light blue-green water, which merges into the deep blue of the lagoon and thus indicates the gradual passage of the overwashed sand shoals down to the deeper lagoon floor. The northern reef loop has only two passes; its northern curve around Tahaa is unbroken for 18 miles. The southern reef loop around Raiatea has eight passes. The lagoon is from half a

mount at northern end of Raiatea.

mile to two miles wide and has soundings of from 15 to 25 fathoms. If the breadth of the lagoon is considered in combination with the slope of the island spurs, it will be seen that the barrier reef may rise from a foundation at least 1000 feet below present sea level. Indeed, few islands give better warrant than Tahaa for a prolongation of their spur slopes beneath the lagoon, as in Figure 133, in making an estimate of reef depth. It would be altogether gratuitous to assume that either one of this island pair was originally cloaked, as in Figure 18, with a heavy cover of ash deposits, the rapid degradation of which to a circuminsular lowland would, after a slight submergence, give a shallow basis for reef upgrowth, while the more resistant rocks of the island core still retained a strong relief.

The reef is usually narrow; off the east side of Raiatea it is only 20 or 30 feet wide, as in Figure 130; but it is somewhat broadened north of Tahaa, as if by a slight emergence; for it there carries more than 30 small, ragged, wasting limestone islets, two or three feet higher than the reef flat.

FIG. 132—Inner bay of Tahaa; drawn from 2-dot spur of Figure 131.

Shells of the giant clam, Tridacna, were seen in these islets, with the valves opening upward in the position that they normally assume when alive and growing, embedded in reef flats; hence the islets cannot be remnants of wave-heaped beaches. The shoals of overwashed sands with lobate

inner margins here slant so gently into the lagoon that their depth is only three fathoms at half a mile back of the reef. Reef blocks overgrown with corals are, as usual, scattered on the shoals.

Low islands on the Raiatea reef are well developed on either side of the passes, as was long ago noted by Perkins, who wrote: "By a singular freak of nature, nearly every passage is bounded on either side by islets covered with a luxurious growth of cocoanut-trees" (1854, p. 224). I ex-

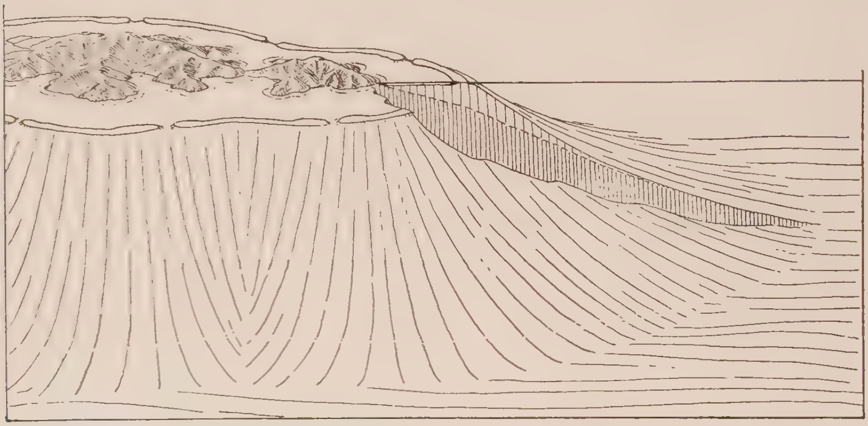


FIG. 133—Diagram to illustrate the great probable volume of the Raiatea-Tahaa barrier reef.

amined six of these islands with some care and found them all to consist of reef débris only. Their accumulation was seen to be due, as has been explained in an early chapter, not to any arbitrary or disorderly freak of nature but to the systematic refraction of the surf at each pass, so that the bent waves approach the incurve of the reef there about as squarely as they approach the long reef front between the passes. Hence the débris that is drifted along the front is stopped on one reef end or the other when a pass is reached, from whichever longshore direction it comes, and thus an islet is in time built up a foot or two above ordinary high-tide level. Even where the islets are overgrown with trees, many coral and shell fragments are brought up by crabs from their burrows.

Great numbers of reef blocks, up to four or five feet in diameter, lie on the widened and shoaled flat near each pass; their surface is blackened by an algous growth, and at a little distance they might be mistaken for volcanic boulders; but on a nearer view their ragged form betrays their composition, and all of the hundreds that I sampled with a hammer stroke gave fractures of clear white limestone. Yet on the several islets that I visited, slabs and cobbles of volcanic rock were occasionally found. Sometimes the slabs were placed as if to serve as a hearth; and I saw no reason to discredit the local belief that such rocks have been carried out from the central island by the natives, nor any reason to accept a contrary belief that ledges of volcanic rock occur on the reef. For, when some

such "ledges" were pointed out by an otherwise intelligent resident who guided me to them, they proved to be nothing more than well cemented reef sand on the margin of a reef island, cut back by the waves. Singularly enough, specimens that were brought to me on Raiatea in support of the opposite assertion that coral rock occurs well up on the mountain slopes proved to be only weathered lava with a whitish, calcareous incrustation.

Views of Agassiz and Marshall

Two statements made by Agassiz regarding Raiatea and Tahaa I must dissent from. One is the presentation of an inference as if it were a fact in the mention of a "submarine plateau [of erosion] extending around the islands, on the outer edge of which the encircling barrier reef is situated" (1903a, p. 160). There is no sufficient evidence that any such plateau or platform exists. The other is an account of the Raiatea reef, as follows: "In the vicinity of all the ship passes leading into the lagoon, either on the east or on the west shore, numerous islands and islets still remain, outliers, indicating the position of the ridges or spurs [of the central island] which have been eroded, and which once extended to the outer edge of the reef flat" (1903a, p. 160). The regular descent of the island spurs excludes the possibility of their standing in any close relation to the reef or its islets; for at the distance of the reef offshore, the spurs should lie, as above stated, at a depth of 1000 feet more or less. Indeed, the occurrence of the reef-sand islands in pairs at the passages makes it altogether unreasonable to relate them to the spurs of the central island. They are sufficiently explained by wave work as noted above.

Marshall, one of the few observers of the Society group who has considered alternative possibilities as to reef origins, writes discriminatingly regarding the last three of its members here described: "It is evident that if the coral reef rises on the edge of a platform of marine erosion this very erosion would have worn the spurs back in such a way that they would terminate in steep cliffs. In no instance . . . that the author observed did the spurs have an abrupt termination. . . . The deep inlets that intersect the coast line of Huaheine, Tahaa and Raiatea are clearly due to stream erosion. . . . The author is therefore strongly of opinion that the absence of cliffs at the termination of the radiating spurs, the presence of deep water in the lagoon, and of far-reaching inlets prove that marine erosion has not had any influence on the form of these islands at the present sea level. . . . The deep inlets appear to be drowned stream valleys and their nature strongly supports the belief that the islands have been subjected to an important movement of subsidence" (1911a, p. 13). The following statement from an earlier paragraph on the same page seems to have lost a negative from its first clause: "This reef [a barrier reef of one of the Society Islands] marks [not?] the edge of the platform of marine erosion as described by Agassiz, but the original margin of the land before depression as described by Darwin and Dana."

Tubuai Manu

A brief account of this hitherto little-known island has lately been published by Chubb (1927a) from which the following items are taken. It is about a mile long and 800 feet high; on its summit the rocks, invaded by dikes, are deeply weathered to clay; the slopes are very steep. The barrier reef, measuring 6 miles from east to west, is surmounted by a nearly complete ring island—a reef débris; the lagoon is very shallow and seems to be floored with calcareous sand. No mention is made of shore-line embayments, which if present at all are probably inconspicuous, owing to the small size of the island.

Borabora, Darwin's and Agassiz' Type Island

The Sculpture of Borabora

Borabora, HO 2005 (Fig. 134), 3 by 4½ miles across and 2379 feet high, is 10 miles northwest of Tahaa. This beautiful member of the Society group is accepted by all who have seen it as one of the most perfect types of a barrier-reef island in the Pacific. It appears to have been originally a single volcano, but it is now much farther advanced in demolition than any of its neighbors above described. A central stock stands up as a bold, cliff-faced, double-peaked mass, from which a number of much lower, round-crested, undulating, and rambling spurs with waste-covered slopes gradually descend to lower levels between broadly open, late-mature valleys. The undulation of the spur crests is a fitting characteristic of the advanced degradation suffered by the island. It is today only the skeleton of the original cone. In strong contrast with Moorea, Huaheine, and Tahaa, which have hollowed-out centers, Borabora has bold central peaks and may be said to foreshadow what Tahiti will become when the lava beds of its peripheral slopes are worn down to subdued forms so as to leave its massive central stock in strong relief above them.

The shore line of Borabora is broadly embayed; some of the outstanding spur crests survive as low-arched lagoon islands, two of which are converted into peninsulas by sand isthmuses. This isolation of spur ends is manifestly a consequence of undulation in the well worn-down spur crests; and herein Borabora differs from the four preceding islands of the group, on which the less degraded spur crests are, as a rule, characterized by continuously descending slopes and in the lagoons of which islands of volcanic rock are therefore rare or wanting.

Although the Borabora spurs are for the most part soil-covered, they occasionally exhibit ungraded lava beds crossing over their crests or slanting down their sides. Small, platform-based bluffs, cut by the lagoon waves, are sometimes seen on spur ends but are best shown on the exposed sides of two little lava islands to the southeast of the main island. Near by I found a small ledge of unquestionable volcanic rock just

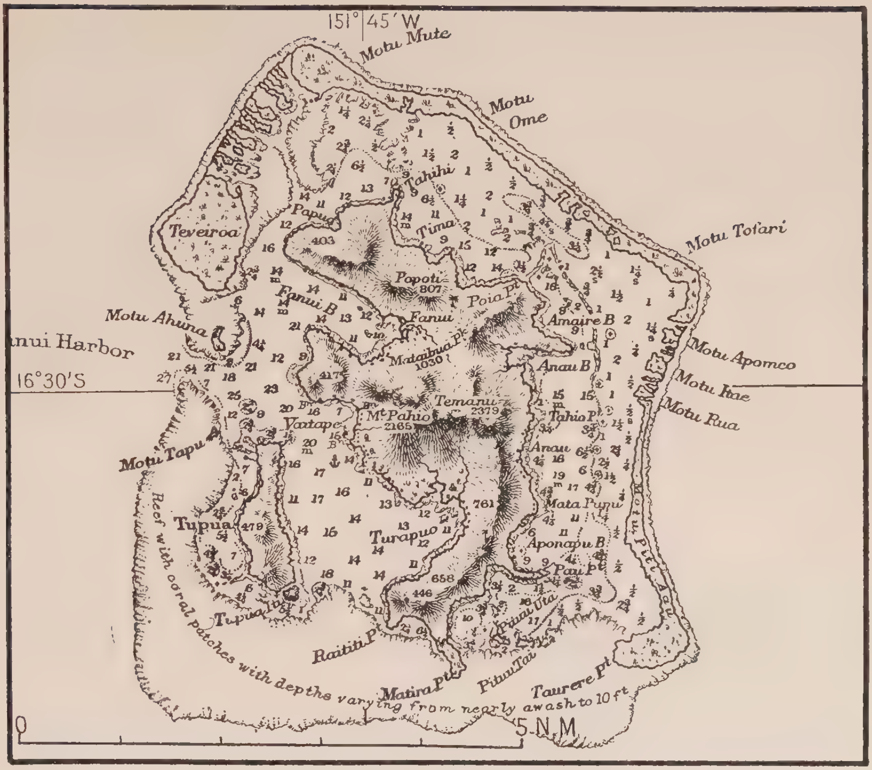


FIG. 134—Borabora, Society Islands; HO 2023.

awash in the lagoon and fringed with corals, one of the very few examples of its kind that was seen in the lagoons of the 35 reef-encircled islands I visited. The ease with which it was recognized satisfied me that my notes as to the absence of visible volcanic rock in the low reef islands of the Raiatea and other lagoons above described are substantially correct. The breadth of the Borabora embayments makes it quite impossible to believe that they were excavated by low-level erosion during the Glacial epochs; and the absence of plunging cliffs on the spur ends makes it equally impossible to believe that the island lost its encircling reef in those epochs.

The Broad Barrier Reef of Borabora

The barrier reef of Borabora is exceptional in the breadth of its flat, which is up to a mile wide. Its northeastern half is largely occupied with palm-covered sand islands. Apparently along with the growth of the wide flat, and perhaps aided by a slight emergence, has gone the extinction of reef passes, of which only one, in the mid-west side of the circuit, remains; and this one is shallower than the lagoon inside of it, where the maximum depth is 27 fathoms. The lagoon floor is distinctly uneven.

The reef flat on the south slants gradually to a depth of one or two fathoms half a mile or a mile back of the reef; its inner margin is lobate, and it has evidently long been encroaching upon the lagoon by the inwash of reef sands. The reef itself is here about 30 feet wide; its level top is covered with small seaweeds. An abrupt descent of two or three feet is made on the inner side of the reef to the shoal of overwashed sands, there dotted with many coral-covered reef blocks.

The islands around the northeastern half of the reef circuit have a width of from an eighth to a three-quarters of a mile; they are all low and flat. Their outer margin lies close along the beach of the reef front; their inner margin is irregular. It is difficult to believe that the islands began by deposition some distance back of the reef front and widened by progradation; widespread inward aggradation by overwash is more probable; but, if so, the islands would appear to represent a former reef flat formed a little below sea level and now slightly emerged, as above suggested.

True-scale cross sections suggest that the depth of the rock floor between the main-island spurs and some of the isolated spur crests can hardly be less than 800 feet and that the depth of the volcanic foundation below the barrier reef must be at least 1000 feet: these measures might be increased to 1200 and 1500 feet without doing violence to the form of the spurs above sea level. Indeed, as it is probable that subsidence has long been in gradual progress during the slow degradation of the island, it is eminently possible that the first-submerged valleys had steeper side slopes than those of the last-submerged spurs; and in this case the total submergence might equal 2000 feet. A similar depth of submergence must be inferred if the upgrowth of the barrier reef has inclined inward instead of being vertical.

Contrasts between Borabora and Tahiti

The continuity and the unusually great width of the Borabora reef flat imply a much longer still-stand of that island essentially in its present attitude than is implied by the discontinuous and narrow barrier reef around Tahiti. Had the only cause of recent reef upgrowth been the Postglacial rise of ocean level around stationary islands, it is impossible to believe that two barrier reefs not far apart in the same region of the Pacific could differ so greatly in surface width and hence in volume as do those of Borabora and Tahiti; for their volume ratios, up from a moderate depth such as 30 or 40 fathoms, are about as 10 or more to 1. They thus teach the same lesson, based on dissimilarity of reef volume, as is taught by the broad Mbengha reef and the narrow Budd reef in Fiji; namely, that in addition to whatever uniform rise of ocean level has taken place in Postglacial time, there have been individual changes of level—in the cases here named, by subsidence—for different islands at different times of different amounts and rates.

Borabora holds a famous position in the coral reef problem. Cook told of its "high, rude and craggy peak"; Lesson gave an enthusiastic account of it, and published an often-copied sketch of one horn of its peak from the other, with the palm-crowned barrier-reef flat far below in the background (1839, Vol. 1, p. 470). Darwin, reproducing Lesson's sketch (1842, p. 3), took Borabora as his type of a barrier-reef island intermediate between the fringing-reef and the atoll stages. Agassiz called it "the

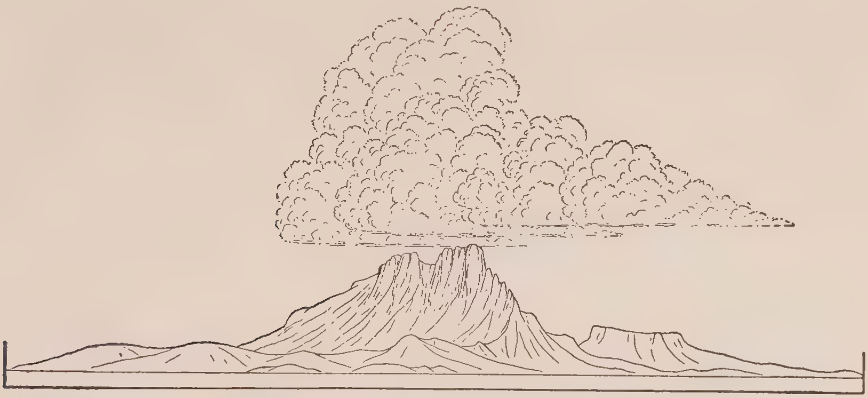


FIG. 135—Sketch of Borabora and its morning clouds, looking north.

most striking of the Leeward Islands" of the Society group, including 20 photo-plates in his account of it (1903a, p. 161), and sent G. C. Curtis to the island in preparation for his making an admirable 14-foot model of it, nature-true in form and color, on a scale of 1:3600, for the Museum of Comparative Zoölogy at Harvard University.

My happy approach to this island over the rounded sea from Raiatea in the early morning was a profoundly impressive experience. Its double summit was crowned with growing clouds (Fig. 135); its broad base of outspread spurs widened farther and farther as they rose over the receding horizon; and the white surf line of the reef finally stretched to double the reach, east and west, of the spreading spurs. Twenty-four hours was not a long time to spend there, but I was well content with the results of the visit on setting out the next morning on the way back to Raiatea. The form of the island is so simple, its origin by long-continued erosion is so manifest, and the relation of the reef to the island is so clearly displayed that their lessons are soon learned. I can agree fully with Agassiz that Borabora gives one of the most "admirable examples and epitomes of the structure and mode of formation of coral reefs of that [Society] group" and that Tahiti and Borabora provide the "key to the structure" of the other islands; but I cannot agree at all that the reefs of Borabora and its neighbors rest on "huge platforms of submarine denudation and erosion" (1903a, p. 135). On the contrary, the island seems to me to present incontestible evidence of great subaerial erosion during long continued sub-

sidence, while its barrier reef was growing up either from an early-cut platform that fronted shore cliffs now completely submerged or from the spur slopes above those cliffs. It thus came to be the perfect type of a subsiding barrier-reef island that Darwin took it to be. Its development is decidedly farther advanced than that of its neighbors on the southeast, to which it forms a highly instructive supplement.

The Surviving Peak of Maupiti

Maupiti or Maurua, HO 2023, 2 miles across and 800 feet high, lies 24 miles northwest of Borabora: it was not reached in my journey. It appears to be the remnant of a single volcano, much reduced by erosion and subsidence, and now surrounded by a reef 5 by 7 miles across over all, but of so great a breadth as to restrict its lagoon to small measure. A single narrow pass opens to the south; the northern half of the reef circuit is occupied by a sand flat. The limited size of the island peak prevents its having any distinct embayments; its strongly eroded features include a bold cliff which falls on the southeast side of the peak abruptly to the shore and apparently plunges below sea level. Three photographs of the island are published by Agassiz, but a better idea of its cliff may be obtained from a drawing by Huguenin in his account of Raiatea (1902, p. 30) referred to above. In view of the prevailing absence of plunging cliffs on the other well dissected islands of the group, it seems less reasonable to regard the one-sided cliff of Maupiti as the work of ocean waves than as of subaerial origin, like the high cliffs of Borabora. For, if that island were submerged far enough to drown its rambling spurs and bring the shore line around its central stock, its residual summit would be even better cliffed than Maupiti. But this explanation of the form of Maupiti would not hold if Agassiz' interpretation were true: he reported that "on the east face of the barrier reef flat . . . numerous outliers of volcanic rocks are scattered, indicating the position and structure of the foundation upon which corals have grown" (1903a, p. 165); also that "the southern and western reef flats are covered with masses of volcanic rocks, the outliers of former volcanic islets and islands once occupying the outer rim of Maupiti" (1903a, p. 138). It would truly be strange if an observer of Agassiz' experience should have mistaken limestone blocks, swept by storm waves from the outer reef face upon the reef flat and there gaining a blackened surface from algous growths, for volcanic rocks, as many less experienced observers have done. Yet in view of his statements about volcanic rocks in association with reef flats on other islands, as noted above, such a mistake seems probable here, where the reef flat stands out so far from the central volcanic peak. Maupiti is therefore interpreted as a nearly submerged island of the greatly eroded, Borabora type; as such it forms a fitting end of the series of volcanic islands that began with Mehetia at the eastern limit of the Society group. Indeed, the very fact

that Maupiti does thus end the series is, to my view, a strong reason for interpreting it as here proposed.

The Northwestern Atolls

The reason for accepting the above interpretation of Maupiti is strengthened when it is recalled that, farther to the north and west, four small atolls are found, which end the series that began in Mehetia even better than Maupiti does itself. There must surely be some causal relation between the formation of volcanic islands by eruption, their gradual disappearance by erosion and subsidence, and the development of fringing reefs, barrier reefs, and atolls upon them.

Regarding one of the northwestern atolls, Motu Iti, Agassiz noted: "Of course the nature of the foundation base of this atoll is problematical. Judging by the character of the other islands in the vicinity, the underlying rocks of the reef flats are probably volcanic" (1903a, p. 165). Regarding another, Tetiaroa, which lies to the east of Borabora and to the north of Tahiti—this being the one atoll that I saw in 1914, and only from a passing steamer—his statement is more definite, even though its assertions are only inferences: "The central peaks have been completely eroded, leaving only the volcanic submarine platform, on the outer rim of which the coral sand islets and islands have been thrown up and have enclosed a shallow lagoon." Then, taking no account of shore-line embayments in the high islands as indicating subsidence and still less of the need of subsidence as an aid in disposing of outwashed detritus, he continues: "Disintegration and erosion are quite sufficient to account for the difference of condition of these . . . island groups without having recourse to special elevation or to individual subsidence" (1903a, p. 167). It is thereupon natural enough that he should have regarded the several members of the Society group as still-standing islands, showing "the steps which characterize the successive stages of denudation and of marine erosion."

Summary for the Society Islands

Yet when the surface forms of the different members of the Society group are closely examined, no scheme from which island subsidence is omitted can be accepted for the explanation of their reefs. And when it is found that the 12 members of the group exhibit so precisely the systematic sequence of island and reef forms that is called for under the subsidence theory, it is then legitimate not only to regard the theory as well supported but also to use it in interpreting the history of the group. It is therefore here concluded that the volcanic rocks seen in eight islands and inferred to exist under the others represent islands, the eruptive construction of which migrated eastward with the passage of time, and which have, since their eruptive construction, suffered erosion and subsidence proportional to their age.

The Austral Islands

The Austral Islands lie south of the Society group. Little physiographic information is to be obtained concerning them, apart from that given on their charts. Two of them are here described. Vavitao, HO 2228, 4½ by 1½ miles, 1434 feet high, has a broad fringing reef around its non-cliffed shore and is encircled by a strong barrier reef, measuring 7 by 4 miles over all, with a reef flat up to 2 miles wide, enclosing a narrow and shallow lagoon. Whether its shore line shows delta-filled embayments is not clear. This island is of especial interest as its position in south latitude 24° makes it the southernmost barrier-reef island in the Pacific. The breadth of its fringing and barrier reefs is of significance in this connection in showing that, even near the southern margin of the coral seas, good opportunity has been given for the Postglacial repair of whatever damage was done to the earlier formed reefs by low-level erosion in the Glacial epochs.

Tubuai, not far to the west of and nearly as far south as Vavitao, HO 1999, 4½ by 3 miles, 1309 feet high, appears to have been formerly embayed, but the embayments are now filled with delta flats which give the island a simple shore line. It has a good barrier reef, 8 by 5 miles over all, enclosing a shallow lagoon from 4 to 6 fathoms in depth, much beset with reef patches. Here again the opportunity for Postglacial reef repair of earlier formed reefs appears to have been good. A few soundings north of the reef indicate the occurrence of a shoal there; hence this island may stand so near to the margin of the coral seas that its Preglacial reefs were for a time cut away, yet not far enough to permit the cliffing of the island itself. Rurutu is described in the chapter on elevated reefs.

Vanikoro in the Santa Cruz Group

The Santa Cruz group, north of the New Hebrides and east of the Solomons, includes several young and small volcanic islands, as well as the larger and embayed but reefless island of Ndeni. It includes also the more normal island of Vanikoro, HO 1985 (Fig. 136), 8 by 7 miles, 3031 feet high, with a 6-mile dependence on the south and a 3-mile satellite close by on the northeast; and it may therefore be regarded as a triplet of volcanic cones. All three cones are well dissected; all have moderately embayed shores, although formerly larger embayments have apparently been diminished by delta growth. Narrow fringing reefs border the noncliffed headlands. A well formed barrier reef surrounds the triplet and encloses a mile-wide lagoon, in which several soundings on the northeast of the island show the unusual depths of 52, 54, and 56 fathoms. Utupua, not far northeast of Vanikoro, HO 1985, 6 by 5 miles, 1240 feet high, is incompletely surveyed, but it has a long bay, 40 to 45 fathoms deep near the mouth, and is surrounded by a 2-mile reef.

Barrier Reefs in the Caroline Group

Kusaie, the easternmost member of the Caroline group, HO 5420, 8 by 9 miles across, 2100 feet high, appears to be a well dissected volcanic island, the drowned-valley embayments of which have been filled by delta plains so that its shore line is now of relatively simple pattern. It is encircled by a reef which is a rather wide fringe on the east coast and a

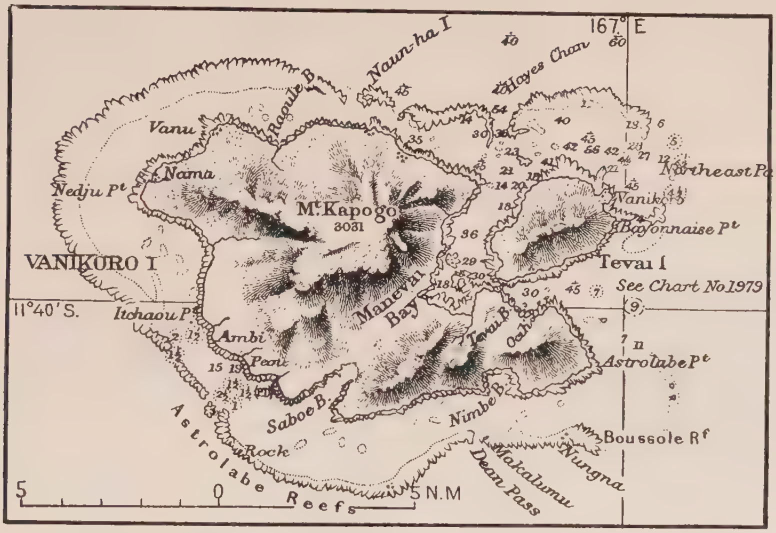


Fig. 136—Vanikoro, Santa Cruz Islands; HO 1985.

near-by and broad barrier elsewhere; no soundings are given in the lagoon. Agassiz stated that the delta plains enter "deep valleys centering towards the middle of the island"; and he noted regarding the reef flats that "the greater part of the corals on the flats themselves have been killed by the volcanic silt washed down the deep valleys" (1903a, pp. 333, 336).

Ponape, HO 425, 10 by 13 miles across, 2539 feet high, is, like Kusaie, a well dissected volcanic island, but its shore line is much more irregular, and its lagoon, enclosed by a wide barrier reef, is peculiar in containing a good number of hilly volcanic islets. The topography of this island is not so well shown on the Hydrographic Office chart as on a map published in the *Mitteilungen aus den Deutschen Schutzgebieten* (Vol. 22, 1909, Pl. 4). Agassiz explains the barrier reefs of both Kusaie and Ponape as mere veneers on platforms of volcanic rocks, planed off by the sea (1903a, pp. 338, 342); but in the absence of shore cliffs and in the presence of shore-line embayments, it seems preferable to regard the reefs as upgrowths on the submerged volcanic slopes. An atoll, Andema or Ant, 3 by 5 miles across, lies only 10 miles to the southwest of Ponape; the reef is

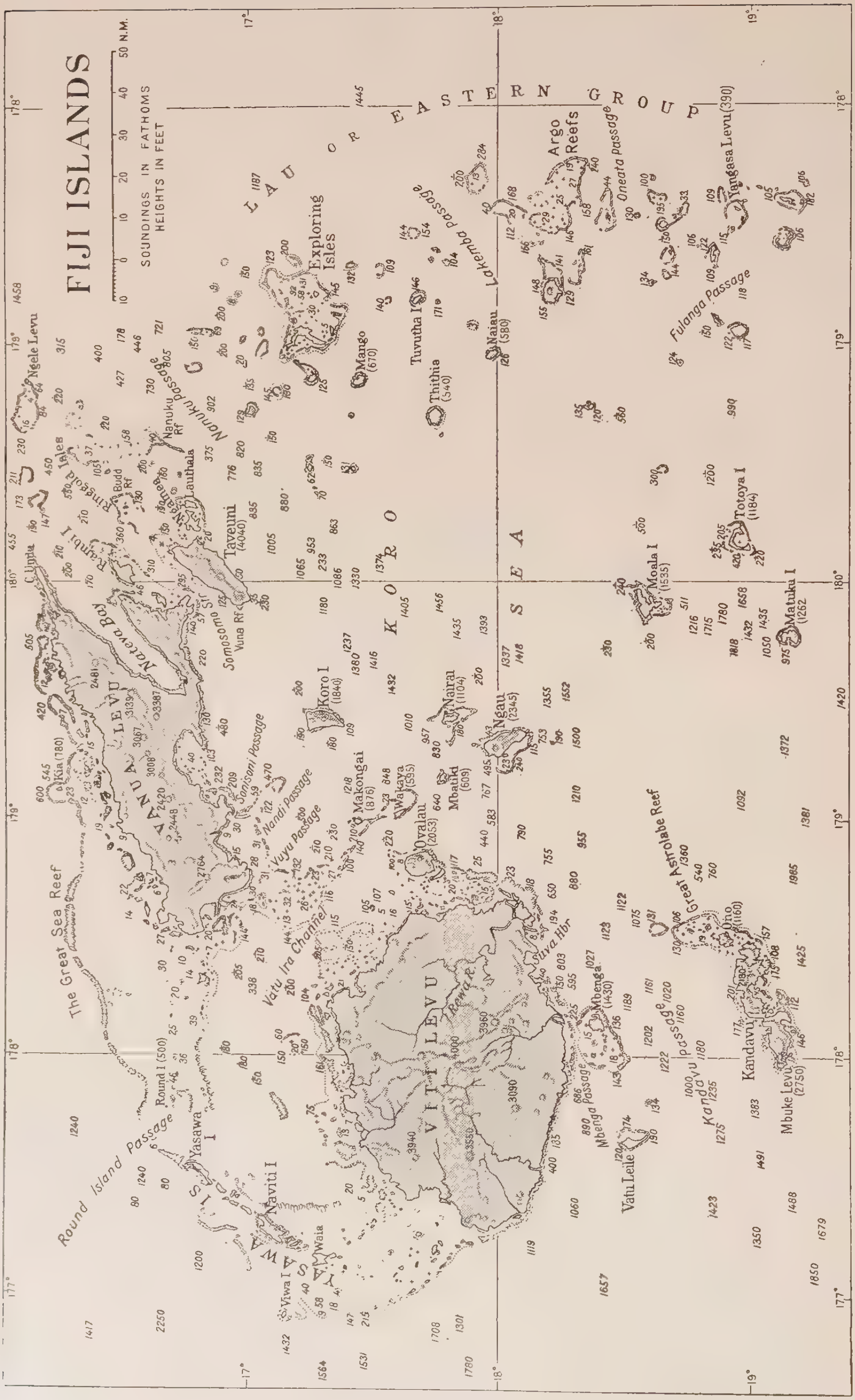


Fig. 137—The Fiji Islands; HO 2021.

narrow and the lagoon is 34 fathoms deep. The atoll foundation has presumably shared in any movement that Ponape has suffered.

Yap, HO 5421, 5 by 13 miles, 585 feet high, is in the western Carolines and has been described by Volkens (1901). It deserves especial mention as apparently representing a more mature stage of reef broadening, as if during a prolonged still-stand of the island, than is usual in the Pacific. The island is presumably of volcanic origin; it has a well dissected form and an irregularly embayed, non-cliffed shore line; but it has no lagoon. The broad reef flat, extending two miles or more outward from the shore, is intersected only by branching water passages.

Barrier-Reef Islands in Fiji

Dana visited the Fiji group as member of the U. S. Exploring Expedi tion under Wilkes and gave a general account of it in his report on the Geology of the Expedition (1849). Apart from special articles to be referred to later, the best recent accounts of the Fiji reefs are by Gardiner (1898), Agassiz (1899), Andrews (1900), and Foye (1918). Foye is the only one of the four who gives adequate consideration to unconformable reef contacts and embayed shore lines as evidence of changes of level. My own observations in Fiji included the brief or more detailed examination of 18 islands. The chief results gained by me are summarized in an article already published (1920a); they will be here presented in somewhat greater detail. Only the barrier-reef islands of the group will be described in this chapter.

The Large Islands of Viti Levu and Vanua Levu

Geology and Physiography

The two largest and most mountainous islands, Viti Levu, HO 2857, 2858, 2859, and Vanua Levu, HO 2855, 2856 (Fig. 137), lie to the northwest of the many smaller ones. The first measures 78 by 57 miles, with a maximum elevation of over 4000 feet; the second, about 90 by 30 miles, with somewhat less height and with the large Nateva Peninsula joined on the southeast. Much geological information about the second island is given by Guppy (1903), but his conclusion that it records "one long story of emergence" (p. 373) is not acceptable. Continental rocks are believed to occur in the interior of Viti Levu, but most of its area and all of Vanua Levu are occupied by volcanic rocks; none of the volcanic mountains, however, exhibit forms of recent eruption; they seem to be deeply eroded, as in Figures 138 and 139. Viti Levu has had a varied history, as is shown by the geological studies of Andrews (1900), Woolnough (1903, 1907), Foye (1918), and Brock (1924): there have been several periods of volcanic eruption alternating with periods of erosion on the land and of deposition in the encroaching or retreating sea, as de-

termined by various changes of island level. Foye infers similar changes of level for Vanua Levu.

The most recent changes of level on Viti Levu are shown by the so-called "soapstone," or well stratified, imperfectly consolidated volcanic muds that flank the southeastern coast. They are described by Cochrane (1911) as reaching heights of 2000 feet. Their fossil fauna has been described by Brady (1888) and Mansfield (1926); the former states that

FIG. 138—West side of Mbutha Bay, east side of Nateva Peninsula.

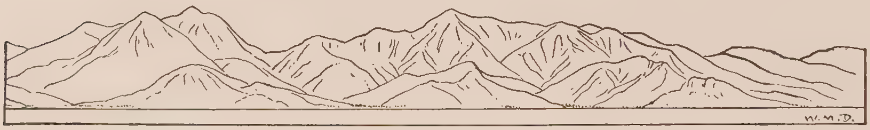


FIG. 139—North coast of Vanua Levu, Fiji, east of Lambasa.

of 97 species of fossil foraminifera 87 are still living in the adjoining sea; they indicate a depth of deposition between 150 and 200 fathoms in Post-Tertiary time. As the soapstones are believed to rest unconformably on their volcanic foundation, a stand of the land about as high as now, perhaps higher, must have preceded the subsidence that permitted their deposition. The surface of these beds is now maturely eroded to moderate relief, and their shore line is embayed by the lagoon of the fine barrier reef that rises off the southeastern coast. Suva, the capital of the archipelago, lies here on a reëntrant of the shore line, with a lagoon harbor to which a pass in the barrier reef gives entrance. The emergence that placed the soapstones above sea level probably did not affect all parts of the large island alike, for they do not appear to occur at the same altitude all around it. The embayment of the soapstone slope on the southeast coast may be in part the result of Glacial changes of ocean level.

In spite of various changes of level the shore line of Viti Levu is not conspicuously embayed; but this is because the many and large embayments that would have entered its valleys in consequence of the latest submergence are now for the most part filled with the deltas of the good-sized or large rivers that drain off the heavy rainfall of the island. Foye (1918) gives an outline map showing the delta of the Navua, a good-sized river not far west of Suva, extending several miles inland; he also gives a similar map for Lambasa valley on the mountainous northern coast of Vanua Levu, where a delta plain fronted by mangrove swamps, in part shown in Figure 140, occupies a former embayment with a width of two or three miles between the valley-enclosing hills. The maturely

dissected mounts over the flood-plain head of this delta are drawn in Figure 141. The valleys thus submerged and buried, as well as their non-submerged inland extensions, appear to be much too wide for excavation by low-level erosion in the Glacial epochs; hence their submergence is ascribed to island subsidence of relatively recent date. It is in association with this subsidence that the barrier reefs of the two large islands appear to have grown up. If this be true, then Glacial changes of ocean

FIG. 140—The broad, delta-filled bay of Lambasa, north coast of Vanua Levu, Fiji.

FIG. 141—The Three Sisters, volcanic mounts at head of Lambasa delta, Vanua Levu.

level have merely played up and down on the reef slopes, permitting them to be alternately eroded and repaired but not initiating their formation.

The Barrier Reefs of Viti Levu and Vanua Levu

The barrier reefs of Viti Levu and Vanua Levu are very unequally developed on different sides of the islands. Thus the fine barrier running offshore around the southeast coast of Viti Levu becomes a fringe (Fig. 142), with deep water outside of it, for some 30 miles around the southwestern curve of the island. It has already been noted that the absence of plunging cliffs along the coast back of this close-set reef speaks strongly against the killing of the reef corals and the occurrence of low-level abrasion here in the Glacial epochs. The fringe departs from the shore at the

FIG. 142—Fringing reef, southwest coast of Viti Levu, Fiji; HO 2857. The right-hand excerpt is farthest southeast; the left-hand, farthest northwest.

western curve of the island, and the barrier again developed there (Fig. 143) gradually sinks below sea level and continues as a submerged barrier for 30 miles. With the submergence of the barrier, the extension of the broad lagoon floor margined by it gains the unusual depth of 58 fathoms. This proclaims a recent subsidence there, too rapid for reef upgrowth, as has been pointed out on an earlier page. The submerged barrier reef may reappear farther on in the imperfectly surveyed reef that seems to loop around the outlying chain of the Yasawa Islands, 40 miles in length, which, according to Foye, "offer some of the best examples of embayed topography to be seen in Fiji" (1918, p. 17). Still farther north two isolated soundings of 80 fathoms are charted in open sea.

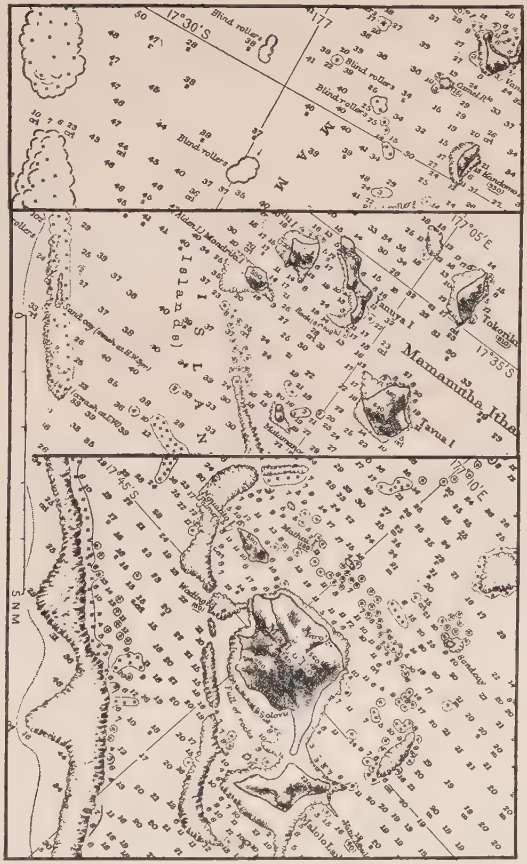


FIG. 143—Submerged barrier reef and deepened lagoon floor, northwest of Viti Levu; HO 2857. Two 3-mile spaces are omitted.

Yet, in spite of the evidence of instability thus found and in spite of the lack of independent local evidence for the killing of reef corals and for the occurrence of low-level abrasion at a standard depth in the Glacial epochs, this large, sloping-floored, and imperfectly enclosed lagoon north of Viti Levu is included in Daly's tables (1915), which are taken to disprove Darwin's postulate of subsiding foundations below upgrowing reefs and to support the Glacial-control theory with its postulate of still-standing islands. A few years after the publication of Daly's table, Foye gave geological evidence of various changes of level northwest of Viti Levu, with erosion at times of emergence. The latest change that he inferred was "a slight tilting of the lagoon [floor?] in recent times toward the northwest, but the lagoon [floor?] and its bordering reef did not originate with this movement. It is a much older feature" (1918, p. 17). This confirms my inference, given above, from the lagoon soundings.

The southeastern barrier reef of Viti Levu, east of Suva, is nearly smothered by the advancing delta of the Rewa River, which discharges an immense volume of muddy water when it is in flood. Guppy states that according to charts of 1840, 1875, and 1897 one of the delta points advanced between 500 and 600 yards in 57 years. Gardiner concludes that delta advance is now taking place upon an area of coral growth, for the bed of one of the river distributaries "is for some distance clean

FIG. 144—The northeast end of Vanua Levu, Fiji; HO 2851.

and hard, appearing to be formed of reef-rock" (1898, p. 448). Still farther east the reef turns northward off the eastern side of the large island and then, still trending northward, passes outside of the adjoining and much smaller island of Ovalau. North of that island the reef is wanting for some 15 miles, as will be more particularly told after Ovalau is described in a later section. Then, beginning again near the north coast of Viti Levu, the reef continues in irregular and discontinuous fashion off the north coast of the island.

The barrier reef around Vanua Levu is of divers patterns. If one passes eastward along the north coast of the island, the barrier reef becomes a fringe at the easternmost salient, Cape Undu (Fig. 144). Next southeast the reef again becomes a barrier and loops around the outstanding island of Rambi. While I was passing Rambi (Figs. 102, 145) and Cape Undu in a trading steamer, it seemed utterly impossible to accept Agassiz' conclusion that "the Rambi plateau [lagoon floor] . . . as we may call the eroded extension of . . . [Vanua Levu] is another admirable example of the mode of formation by submarine erosion of such plateaus" (1899, p. 130). Submarine erosion independent of changes of island level cannot possibly be held responsible for the production of the well embayed shore lines seen thereabouts. But it was equally impossible to accept Guppy's view that the history of Vanua Levu during the formation of its reefs is "one long story of emergence" (1903,

p. 373) or Murray's theory that the reefs here so strongly yet so variably developed have grown outward from the shore of stationary islands. Daly's later proposal that these reefs rest on a platform of low-level abrasion was no more acceptable, because of the absence of shore cliffs back of the narrow Undu fringing reefs and also because the lagoon floor back of Rambi cannot have been accessible to the waves of the lowered Glacial ocean. Only one other theory of reef formation remained; and that one was so completely competent to account for all the

FIG. 145—Northeast end and northwest side of Rambi, Fiji.

coast and reef forms as consequences of the unequal subsidence of a maturely dissected land surface that its acceptance seemed unavoidable.

On the northwest side of Vanua Levu, the barrier reef, after making a 5-mile outward turn around the small island of Kia (Fig. 7), sweeps far westward in an incompletely surveyed loop, nearly 50 miles long and 30 miles across, as if to include the small and distant Round Island, 500 feet high, with a lagoon depth of 46 fathoms near it. Two smaller loops, each about 25 miles in length, make out from the western part of southern Vanua Levu, as if again to include small outlying islands.

Origin of the Lagoon-Floor Plains

The lagoon floors in the above-described barrier-reef loops are of ordinary depth for the most part. They are plains of large extent. The main islands do not possess such plains, except in their deltas of much smaller area; but the lagoon floors cannot be submerged delta plains, because their outlines are not such as deltas could assume. The outlying islets that rise from the lagoon floors strongly suggest that the lagoons cover submarine extensions of the larger islands, from the now submerged shores of which the barrier reefs grew up and over the surface of which the lagoon sediments were spread. In view of the change of the reefs from fringes in certain districts to far-removed barriers in others, the reef-promoting subsidence must have been of unlike measure and rate in different parts of the island circuits. The most rapid subsidence may well have been northwest of Viti Levu, where the barrier is submerged and the

lagoon floor has an exceptionally great depth. Subsidence of unlike measure and rate is perfectly consistent with the history of the large islands, as worked out from their geological structure by the observers above cited. The smooth lagoon floor around Rambi (Fig. 102) deserves special consideration in this connection.

The Smaller Barrier-Reef Islands of Fiji

The Stellate Island of Ono

An irregularly stellate outline is exhibited by the island of Ono, HO 2858 (Fig. 146), a well dissected, well embayed, single volcano in the south-

FIG. 146—Ono, Fiji; BA 167.

western part of the group, 3½ miles in diameter and 1160 feet high, with low bluffs and narrow benches nipped on its spur ends. This island, instead of having a barrier reef of its own, is enclosed, very imperfectly on the northwest, by a northeastward extension of the barrier reef which comes from the south coast of the near-by and much larger island of Kandavu, next to be described. A sail around Ono enabled me to outline its bay heads back of their delta plains, as in the above chart; a visit to its chief western bay (Figs. 147, 148, and 149) impressed me with the evidence of subsidence there presented.

The Well Embayed Island of Kandavu

Kandavu, the southwesternmost member of the Fiji group, HO 2858 (Figs. 150 and 8), 32 miles long by from 3 to 8 miles across, with summits from 1400 to 1800 feet high, has a fine barrier reef off its south shore, where the enclosed lagoon is up to 3 miles wide and has depths up to 22 fathoms.

Fig. 148

Fig. 149

Fig. 148—Looking into bay, west side of Ono, Fiji.

Fig. 149—Entrance and head of bay, west side of Ono. (Photograph by Stinson, Suva, Fiji.)

Off the north coast the reef is mostly wanting. Both coasts of this island were examined along good parts of their length on two visits in cutter sloops. Tavuki Bay, a branching reëntrant (Fig. 151), and its near-shore reefs west of the John Wesley Bluffs on the north coast were examined with some care. The bay is a typical group of drowned valleys, like many another by which Kandavu is beautifully indented. The bay branches are filled with deltas fronted with sandy beaches that slope off to mud flats; the subdividing spurs are slightly cut back in low bluffs fronted by low-tide rock platforms. Forward from the bay beaches and

FIG. 147—West side of Ono, Fiji.

spur bluffs are broad fringing-reef flats, on which the outwash from the deltas appears to be encroaching. Seemann noted that in this bay "at ebb tide one has to walk about half a mile over the coral reefs before being able to reach the boats" (1862, p. 140). The reefs, especially a reef point that advances in the middle of the bay, bear an abundance of blackened limestone blocks, on which a hammer blow always revealed white limestone. Volcanic blocks were seen only close to the spur-end bluffs. Hence I cannot agree with the latter part of Agassiz' statement: "The heads studding the Bay of Tavuki, and forming the extension of the outer reef patches parallel to the coast, are covered with thriving corals, growing on a substructure of volcanic rocks, as is clearly seen from the nature of the negro-heads cropping out in the bay" (1899, p. 28). Judging by the form of the spurs and the breadth of this bay and several others, 500 or 600 feet would be a moderate estimate for the depth of submergence the island has suffered. If the John Wesley Bluffs, of which Agassiz gives a good photograph (1888, Pl. 50), and other lower bluffs farther east on the north coast, are the result of low-level abrasion during a temporary failure of reef protection, as I believe may prove to be the case, the failure must have been local in view of the absence of similar plunging cliffs on the south coast; hence the failure of reef growth here cannot be explained by a reduction of ocean temperature in the Glacial epochs. The many bays of the island are too broad to be the work of low-level erosion in those epochs. The subsidence of the island seems to me unquestionable.

Murray on Kandavu

The most noteworthy thing about Kandavu is not to be found in its beautifully sculptured form or in its strongly embayed shore line or in its

FIG. 150—Middle part of Kandavu, Fiji; BA 167.

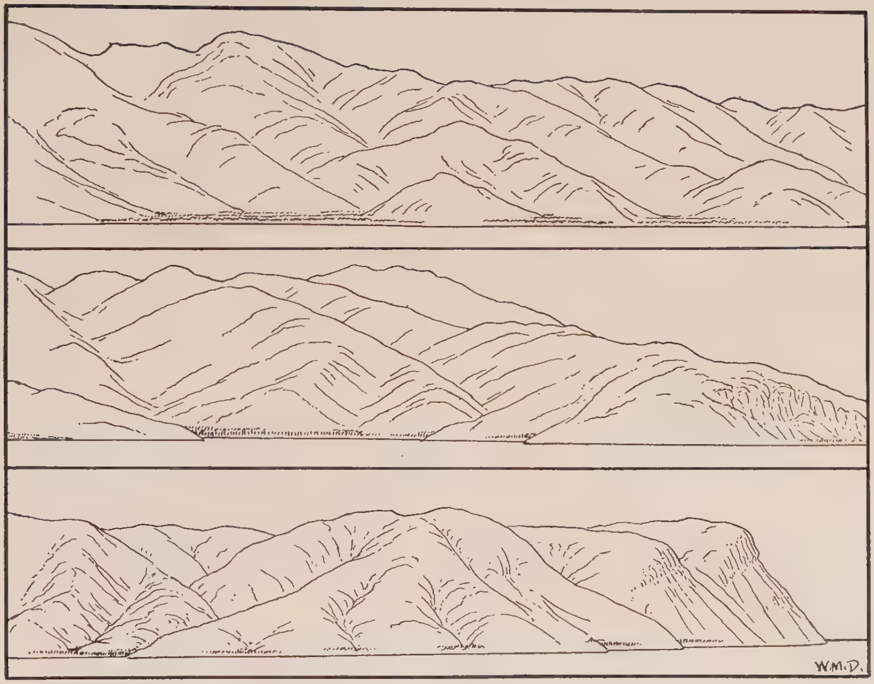


FIG. 151—Upper view, looking across Tavuki Bay, north coast of Kandavu; middle view, looking into Tavuki Bay; lower view, John Wesley Bluffs; north coast of Kandavu.

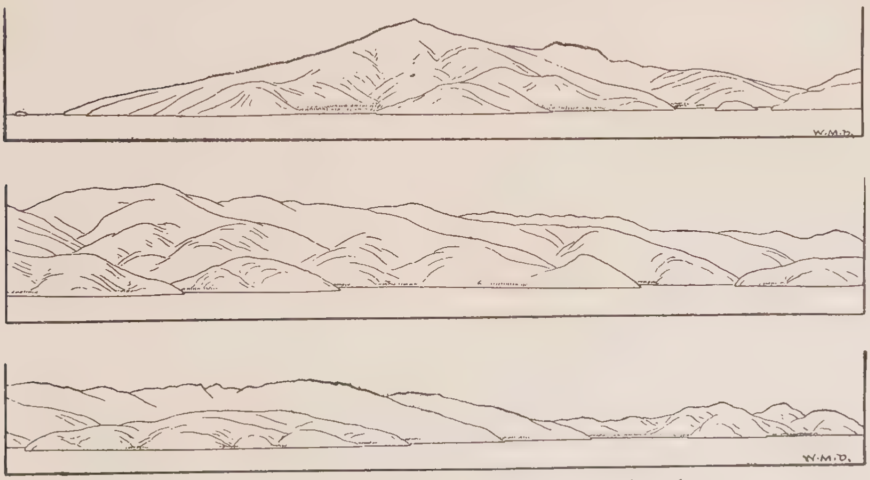


FIG. 152—Three views in Ngâloa Bay on the south coast of Kandavu.

varied reef development but in an extraordinary statement made about the island by Murray. After he had seen it as a member of the *Challenger* expedition, when he visited Ngaloa Bay on the south coast (Fig. 152) he wrote: "It was here that, not being able to apply Mr. Darwin's theory in explanation of the phenomena of the Kandavu reefs, I commenced to doubt it altogether. . . . The more observations accumulate, the more does it seem to me probable that there never was a barrier reef or atoll formed after the manner required by Mr. Darwin's theory" (1889, p. 222). Unfortunately, Murray took no account of island embayments in reaching this conclusion. He thus exemplified the statement here made on an earlier page to the effect that, so long as the reef-encircled islands are neglected and only the island-encircling reefs are examined, almost any theory of reef origin may be accepted. It is the embayed shore line of Kandavu and not the mere existence of reefs around it that demands subsidence.

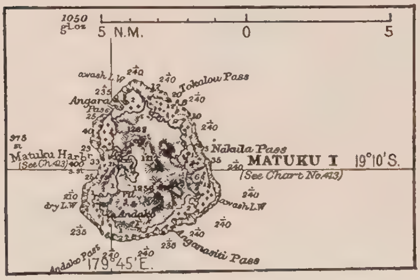


FIG. 153—Matuku, Fiji; HO 2852.

The Ngau Belt of Barrier-Reef Islands

A north-south belt of barrier-reef islands in central Fiji, most of which were, along with the southwestern islands of Ono and Kandavu, visited during my voyage of 1914, is next selected for concise description as affording repeated evidences of island subsidence during reef upgrowth. These islands will be referred to Chapter XVI as constituting the Ngau belt.

Matuku and Its Supposed Caldera

Matuku, the southernmost member of the belt, at the mid-southern border of the Fiji group, HO 413 (Fig. 153), 5 by 4 miles across and 1260 feet high, is elaborately dissected and well embayed, but the embayments (Fig. 155) are much encroached upon by delta flats and mangrove swamps. Fringing reefs are broadly developed around the non-cliffed spur ends; and a strong barrier reef, rising half a mile or a mile offshore, encloses a shallow lagoon much beset with reef patches. A description of the island, in which it is significant that no mention is made of the shore-line embayments, was written for the *Challenger* Narrative by one of the staff, probably by Moseley, as the account is repeated in his own book (1892, p. 254). It is as follows: "From its summit the island was seen to consist of a single crater, the edge of which had been denuded and cut into a series of fantastic peaks, with intervening steep sided gulleys. The ancient crater itself now forms the harbor, the inlet to which is . . .

where the western border has broken down" (1885, Vol. 1, p. 487). A similar opinion was expressed a few years later in the report of the German exploring vessel *Gazelle* (1889, Vol. 3, p. 271). In both these cases the opinions expressed appear to result from a habit of neglecting the results of erosion and of interpreting any great depression in a volcanic mass as a crater.

So far as my own observations went during half a day on the west coast of Matuku, a series of confluent cones arranged on a slightly curved line,

FIG. 154—The west coast of Matuku, Fiji. The two upper views make a panorama as seen from off shore; the lower view is drawn from spur X in upper view.

convex to the east, all well dissected and moderately submerged, would account for the visible features of the island quite as well as, or better than, the supposition that it is part of the rim of a large, single, broken-down caldera. Some of the hornlike peaks have much more the appearance of central stocks in separate cones than of short-sector buttress summits, like those of Huaheine in the Society group. But, whatever the origin of the island in its initial form, it has been well dissected and well submerged, as appears in my sketches. Yet that caldera-ring islands do occur is clearly shown by the next example.

The Caldera-Ring Island of Totoya

Totoya, 18 miles northeast of Matuku, HO 412 (Fig. 154), 5 miles in diameter, 1184 feet high, is a typical example of a caldera ring, breached on the southern side, maturely dissected, and moderately submerged. The inner shore line of the caldera is well embayed (Fig. 156); some of the bays are nearly delta-filled. The island is encircled by a good barrier

reef, up to a quarter mile in width. The lagoon inside the caldera is nearly three miles in diameter and about 35 fathoms deep; outside it is from half a mile to a mile wide and from 20 to 30 fathoms deep. On the north, where the barrier reef is wanting for nearly three miles, the lagoon floor borders on deep water with a depth of 30 or more fathoms.

Agassiz has outlined the successive changes that he supposed would have been brought about on Totoya, "had the denudation and submarine erosion which have brought it to its present state been continued during a longer period of time," the island being assumed not to subside. Further erosion would first change it from a ring island to three separate ridge islands; these ridges would then be reduced to islets joined by coral patches; finally, even the islets might be cut down, leaving "a nearly circular atoll with a [lagoon] depth of 35 fathoms—an atoll with the formation of which subsidence has had nothing to do. . . . A number of such atolls are found in Fiji, the formation of which can be satisfactorily explained on the theory that the ring of coral patches represents the rim of an extinct volcano which has been cut away to below low water mark" (1899, pp. 39, 40).

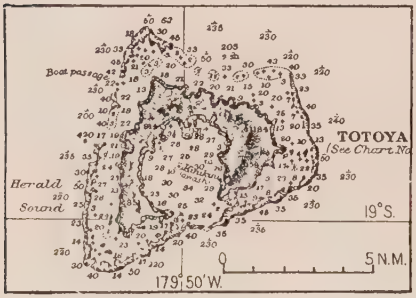


FIG. 155—Totoya, Fiji; HO 2852.


FIG. 156—Interior coast of Totoya, looking north. (Outlined from photograph by Stinson, Suva, Fiji.)

These suggestions unfortunately remain only in the status of unverified speculations, first, by reason of the arbitrary and altogether unwarrantable exclusion of subsidence even as a possibility; second, by reason of the indifference to certain alternative hypotheses in which subsidence is a factor; and third, by reason of the failure to specify critical features by which atolls thus formed may be distinguished from atolls otherwise

formed. On the other hand, certain uplifted and dissected atolls in eastern Fiji exclude the possibility of their consisting of a thin veneer of coral limestone on a truncated caldera rim, as has been shown in Chapter IV; and certain other uplifted reefs in the same region prove, by the unconformable relation of their limestones to the underlying volcanic rocks, that they were formed in close association with subsidence. No uplifted coral reefs in Fiji have been found to lie on platforms of marine abrasion.

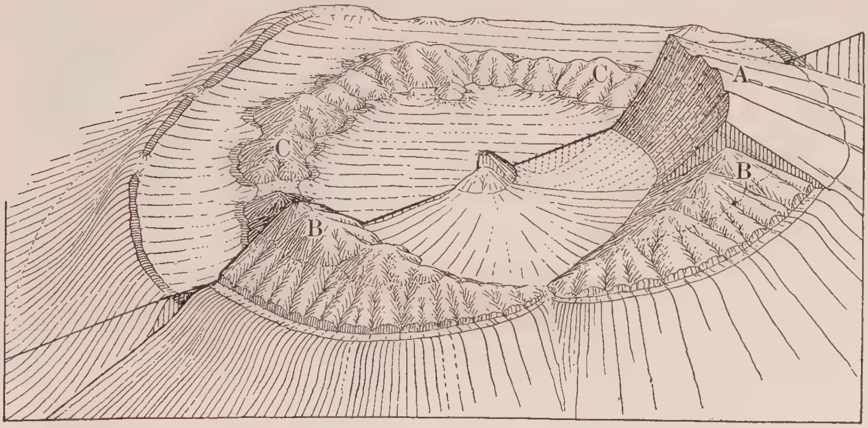


FIG. 157—Diagram illustrating development of Totoya and its barrier reef.

Hence an alternative view, differing strongly from that adopted by Agassiz but supported by everything that I saw during an afternoon and a morning on Totoya and reinforced by many observations elsewhere in Fiji, deserves consideration. It may be supposed that the initial caldera ring, sector *A*, Figure 157, was maturely dissected, sector *BB*, and that small cliffs were at the same time cut around the reefless outer shore line while the inner lagoon was much shoaled; then the island subsided to the level of the dotted contour line in sector *BB*, being thus reduced to a lower and narrower ridge ring with an embayed shore line, as in the background semicircle, *CC*; and at the same time the up-and-out growth of a reef, which was established in consequence of subsidence, transformed a fringe into a barrier. A deep notch that formerly led a water passage through the western curve of the ridge ring was reef-filled, and thus only the southern breach of the ring was left as an entrance into the caldera lagoon. Continued subsidence would completely submerge the ring and transform the barrier reef into an atoll. This sequence of changes is believed to be much more consistent with the processes here and elsewhere operative in Fiji than the production of an atoll by the degradation of a still-standing caldera ring by marine erosion until it is reduced to a depth of 20 fathoms or more and its reef alone survives.

Moala, Ngau, Nairai, and Mbatiki

Moala, HO 109, 25 miles northwest of Totoya, has a massive and moderately embayed main body, measuring 7 by 2 miles, 1535 feet high (Fig. 158a) and a maturely dissected and well embayed southern peninsula (Fig. 158b) measuring 3 miles by 1 mile. The depression holding the east-opening bay between the two parts of the island has been credited

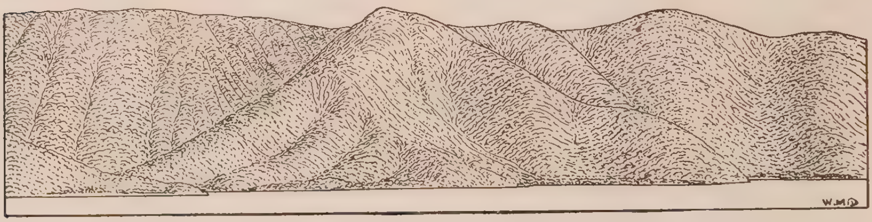


FIG. 158a—The massive plateau of central Moala, looking north.

FIG. 158b—The maturely dissected southern arm of Moala, looking south.

with being a crater, but the only evidence for such an origin is that it is a depression. The island is surrounded by a barrier reef generally half a mile or more in width, enclosing a lagoon from 1 to 2 miles wide and from 15 to 25 fathoms deep. Along 3 miles of the northwest coast the reef touches the island as a wide fringe.

Ngau, 50 miles northwest of Moala, HO 411 (Fig. 161), 11 by 5 miles, 2345 feet high, with an arm enclosing a broad bay on the west, is a fairly well dissected island, probably representing more than one center of eruption. It has moderately developed embayments, the area of which is, as usual, reduced by delta flats (Fig. 162). The surrounding reef forms a fringe up to a mile in width along the east coast but loops around a 3-mile lagoon on the west, where the depths are from 20 to 30 fathoms. The absence of spur-end cliffs along the fringed east coast (Fig. 38), where deep water is charted just outside of the reef, has been referred to in an earlier chapter as proving that this island was reef-protected during the Glacial epochs.

Nairai, 8 miles northeast of Ngau near the center of Fiji, is probably a single, well dissected volcano, HO 111, 5 by 2 miles, 1104 feet high. It is too massive to have large embayments; its valleys have delta flats (Fig. 163) between the hills on either side of their lower course. The surrounding reef has the outline of a three-rayed star, breached between its northern and western points; the lagoon, 15 or 20 fathoms deep, ex-

FIG. 159

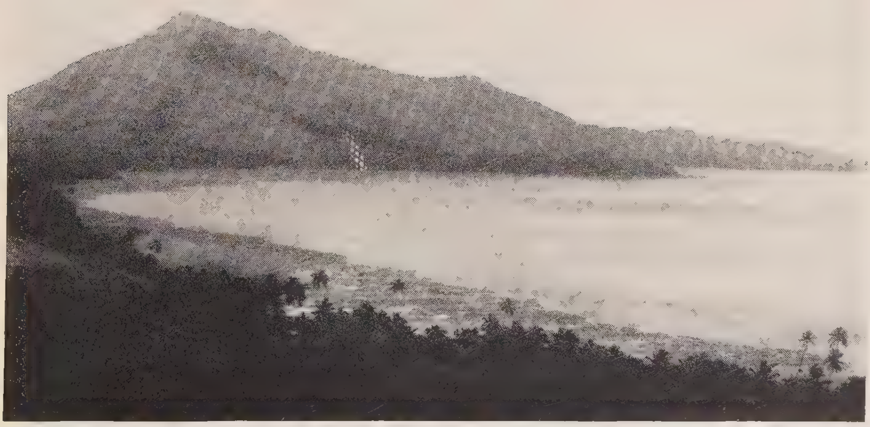


FIG. 160

FIGS. 159, 160—Bay on west coast of Ngau. (Photographs by Stinson, Suva.)

FIG. 161—Northern and northwestern coasts of Ngau.

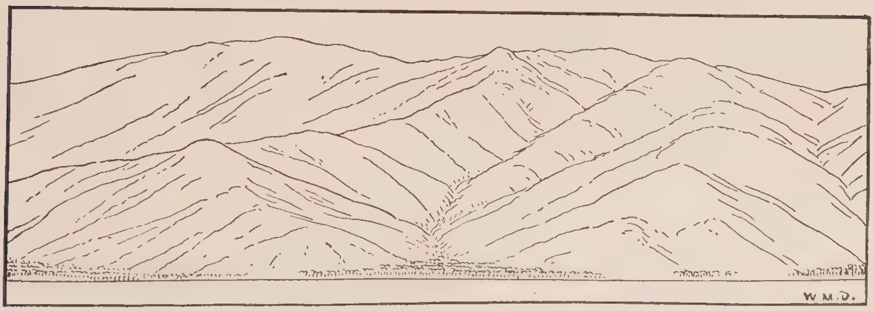


FIG. 162—West coast of Nairai.

FIG. 163—Little Wakaya, as seen from Great Wakaya; Mbatiki in distance.

tends 5 miles from the island in the western ray of the reef. A small volcanic island rises in the southern arm of the lagoon.

The little island of Mbatiki (Fig. 161), 2 miles across and 609 feet high, well embayed, with a close-set barrier reef, was seen on the way to Nairai. It has the appearance of a deeply dissected mountain, almost submerged.

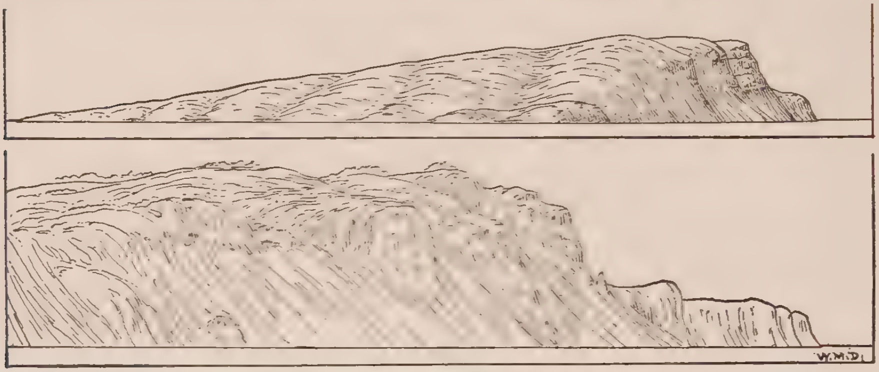


FIG. 162.—Eastern slope and western cliffs of Wakaya.

Wakaya and Makongai and Their Figure-8 Reef

Wakaya, 20 miles northwest of Nairai, HO 2559, is unique in being not a dissected volcanic cone like its neighbors but a pair of up-tilted, lava-sheet fault blocks, 3 by 1, and 1 by ½ miles across and 595 and 310 feet high respectively. Each block has a slightly dissected scarp on the west and a long slope trenched by a number of submature consequent valleys, moderately embayed, on the east. The smaller block as seen

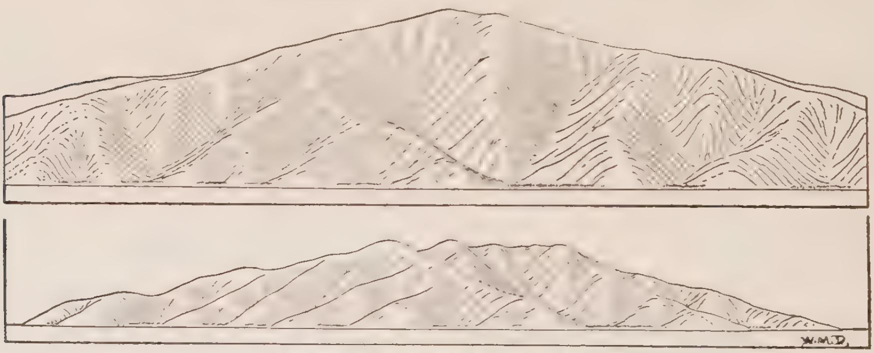


FIG. 163—West coast of Makongai, Fiji.

from the larger one is sketched in Figure 163. A reef, which rises near the base of the scarp on the west, loops around a lagoon from 20 to 30 fathoms deep and 3 miles wide by 10 miles long on the east. If the visible slope of the fault blocks is continued under water, the total north-south block length must be increased from 4 miles to 8 at least,

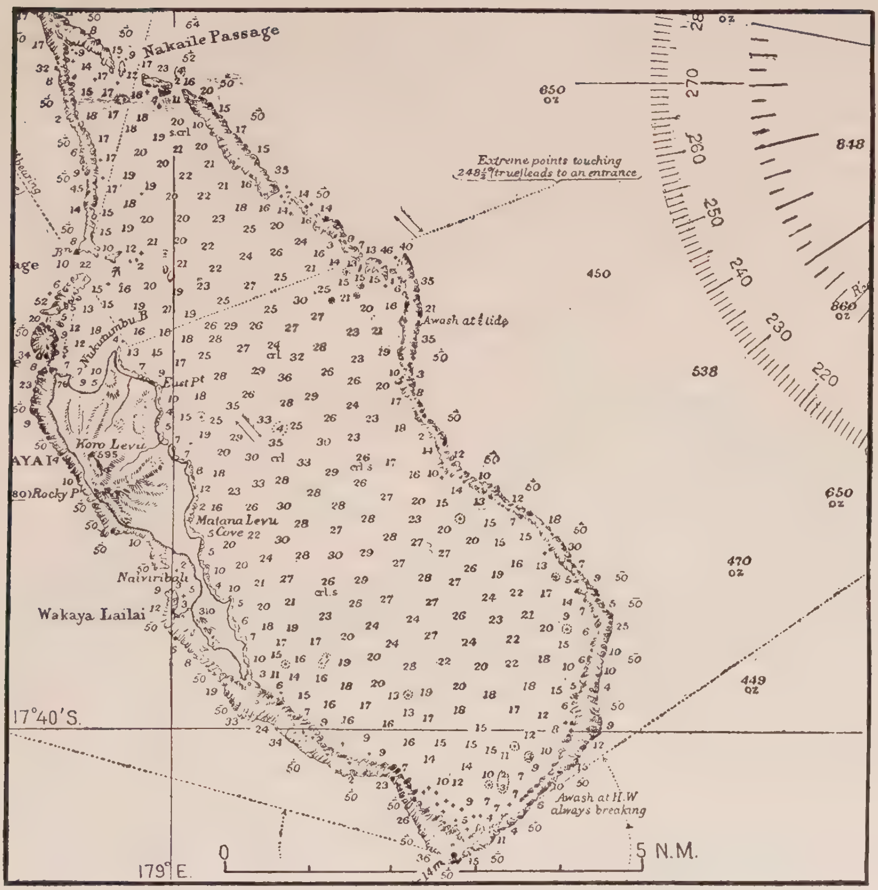


FIG. 166—Wakaya and its unsymmetrical barrier reef; HO 2859.

and the foundation of the eastern reef loop must be 1000 feet or more below sea level, as may be better inferred from the larger-scale Figure 165. Although this is the only example of its kind in Fiji, I feel confident of being right in the above interpretation of its origin, because after a two-day stop there no other interpretation seemed possible.

Makongai, 8 miles north of Wakaya, HO 2859, 2 by 2½ miles, 876 feet high, is a single volcano, maturely dissected and fairly well embayed (Fig. 166) although the bays are much filled with alluvium at their heads. A small satellite, 1 by ½ mile, stands near by on the northwest. The surrounding reef is only about a quarter mile distant on the east but loops around a 2-mile lagoon, 15 to 20 fathoms deep, on the north, west, and south; its northwestern or leeward arc is imperfectly built up.

The eccentric position of Wakaya and Makongai in their reef loops is made all the more striking by the junction of the loops in a figure-8 pattern. Wakaya rises in the western part of its loop presumably because of

its unsymmetrical submarine slopes, shown in section *B*, Figure 167. Makongai probably occupies the eastern part of its loop for a similar reason, as shown in section *A*, although its visible cone does not imply submarine asymmetry so clearly as the visible part of the Wakaya fault block does. Both islands show lightly cut shore lines recently emerged 4 or 5 feet above the level of the lagoon waters.

Koro, east of Makongai, measuring 4 by 9 miles across and 1840 feet in height, lay outside of my route. According to the chart it is peculiar in having a simple shore line and in being surrounded for the most part

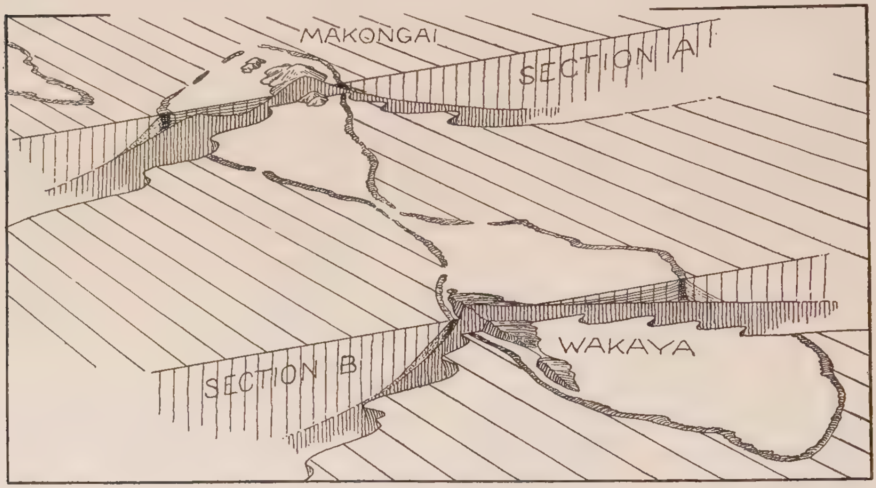


FIG. 167—Block diagram of Wakaya and Makongai with their barrier reefs.

by a fringing instead of by a barrier reef, as if it has subsided less than the islands above described. My only view of the island was from a passing steamer; it presented a massive appearance, as if it were a fault block lately uplifted and little dissected. Its form in no way suggested a group of young volcanic cones, such as constitute Taveuni, or a maturely dissected volcanic mass, like Matuku. The little-carved slopes, the simple shore line, and the narrow close-set reefs in Fiji are exceptional features but consistent with recent uplift, followed by little if any subsidence.

Koro is of historic interest, as it was chosen by Dana as the first member of a series to illustrate increasing measures of subsidence and reef upgrowth. The other members are Ngau, Nairai, Lakemba, Argo, Exploring Isles, and Nanuku; the last-named is now charted as the long Ringgold atoll (Fig. 33) in the northeastern part of Fiji (1849, p. 125). Koro is described also by Cooper (1880), Gardiner (1898), and Agassiz (1899).

Ovalau, a Near Neighbor of Viti Levu

Ovalau, HO 2861 (Fig. 168), 5 by 7 miles across and 2000 feet high, lies 8 miles from the mid-east coast of Viti Levu and the same distance south-

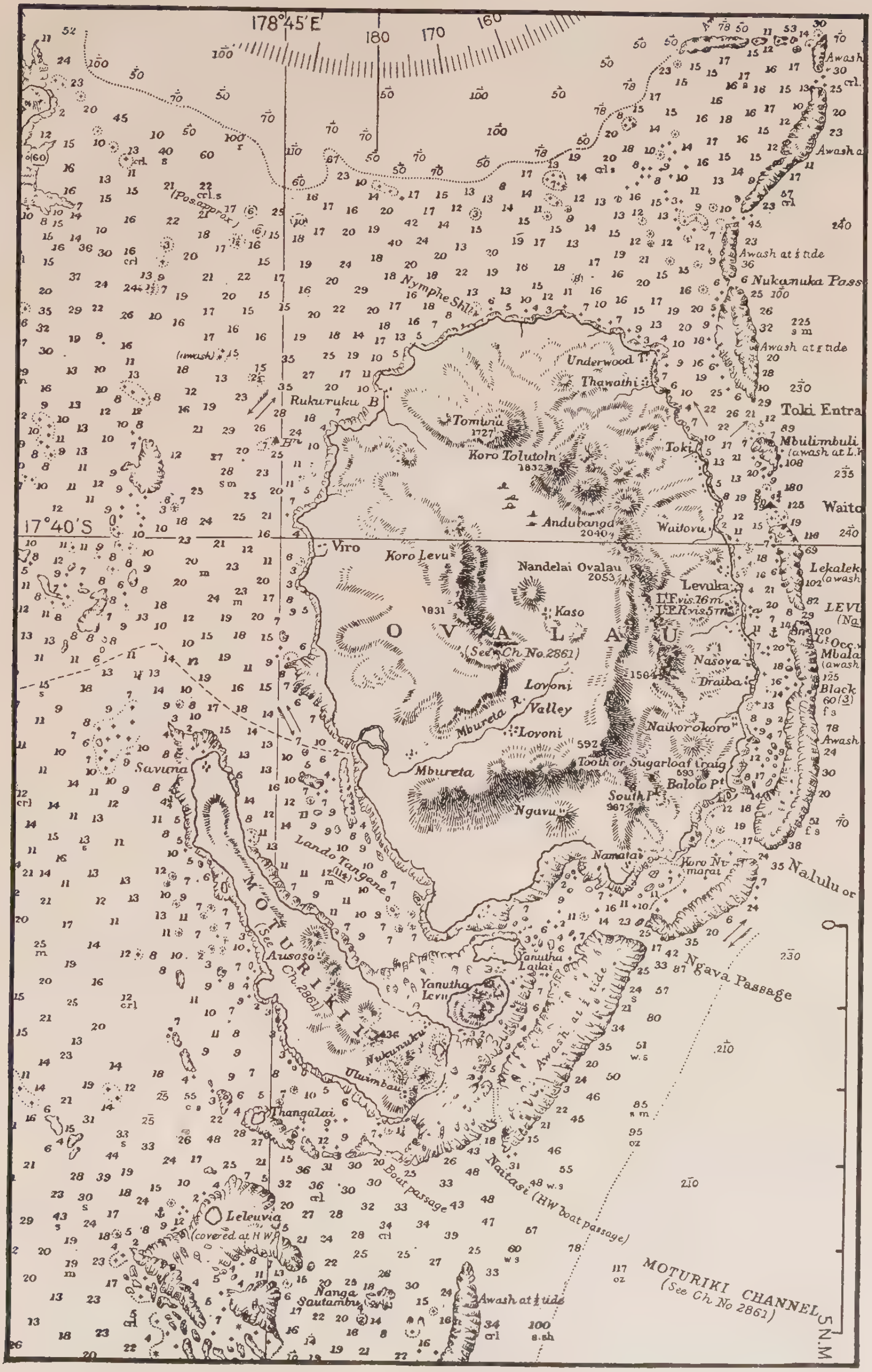


FIG. 168—Ovalau and its lagoon, Fiji; HO 2859.

west of Wakaya. It looks like a submaturely dissected caldera, breached on the northwest. Its embayments, filled with delta flats, are of moderate size because its exterior valleys are short and steep. The erosional origin of the valleys is clearly shown by the outcrops of lava beds or agglomerates on their sides, as in Figure 23. The irregular degradation of the spurs not infrequently produces knobs of bold slope on their slanting crests. If such a knob happens to lie just over the present shore line, its bold shape takes on the appearance of a sea cliff (Fig. 169); but that the slope is essentially of subaerial origin is clearly shown by the prevailing absence of similarly bold slopes on other spur ends. There is, however, a small measure of wave work observable on the headlands, where a low, wave-cut bluff occasionally overhangs a narrow rock bench. As on Wakaya and Makongai, the bench, still bearing gravels, is now emerged 4 or 5 feet above the present shore line (Fig. 169). It is evidently possible that a slight emergence of a lightly cut shore line might be produced by tide reduction in a lagoon consequent upon barrier-reef upgrowth after a rapid subsidence, in accordance with Johnson's principle. But the range of ocean-shore tide in Fiji is so small that its reduction to lagoon tide by this process seems insufficient to explain the measure of emergence here observed. It may be due to a fall of ocean level, as Daly has suggested for similar emerged shore lines, or to a rise of the island.

Ovalau is, as already told, enclosed by the barrier reef of Viti Levu, which here departs 15 miles from the east coast of that much larger island. The lagoon outside of Ovalau is half a mile wide and 20 fathoms deep; a pass in the reef determines the location of Levuka, the chief town, picturesquely situated on two confluent deltas on the mid-east coast of the island, where I spent several days. A large black rock on the reef south of the pass, which serves navigators as a landmark, was asserted by several residents of Levuka to be "lava," like the boulders that occasionally roll down the mountain slope into the back lots of the town; but, when I went out to the rock, the first blow of a hammer revealed the glistening white of its coral limestone. Several experiences of this sort on different islands made me extremely skeptical as to the occurrence of volcanic boulders on barrier reefs.

Ngamia and Lauthala, Neighbors of Taveuni

It will be recalled that the account of the Fiji island of Taveuni in an earlier chapter stated that, while its southwestern half was crowned with young volcanic cones, its northeastern part was of older origin and well dissected and also that, although a submarine bank adjoins this older part, no well formed barrier reef rises from the bank margin. It may now be added that close to the east of northeastern Taveuni lie two well dissected islands, HO 2851 (Fig. 102), on the eastern extension of the Taveuni bank, but that here the bank margin is reef-rimmed. The islands are

Fig. 169—Bluff and emerged shore line, east coast of Avalau. (Photograph by Stinson, Suva.)

Ngamia, 5 by 7 miles, 1000 feet high, and Lauthala, 2 by 3 miles, 880 feet high; both are well dissected and have pronouncedly irregular shore lines. The surrounding lagoon floor has a width of 1 or 2 miles and soundings of from 20 to 40 fathoms; the enclosing barrier reef, absent on the west toward Taveuni, is narrow but fairly continuous. Mbengha, lying 7 miles off the mid-south coast of Viti Levu, will be described more fully in a later section of this chapter, in connection with the breach on the northern side of its barrier reef.

Ono-i-Lau

Ono-i-Lau, a far southeastern member of the Fiji group, is described by Foye (1918, pp. 61–65) as consisting of three small islands of rolling form, the highest of which is 370 feet in altitude. All three show volcanic beds dipping outward from the center of the little group at angles of 12° or 15° and cut by radiating dikes; they are therefore taken to be the residuals of a maturely dissected caldera, about 3 miles in diameter, partly submerged. A barrier reef, 4 by 7 miles across, encircles the group and bears small remnants, 15 or 20 feet high, of an earlier reef now elevated and much dissected. The subsidence here implied in the formation of the encircling reef is about 1500 feet; a measure that is by no means incredible in view of the demonstrable changes of level experienced by other islands in Fiji.

Breaches in Barrier and Atoll Reefs

It has been noted in the first chapter of this book that barrier and atoll reefs are frequently breached on their leeward side, where the smooth floor of the lagoon, open to the ocean, falls off in a steep pitch by which descent is made to deep water; and on a foregoing page a breach in the barrier reef north of Ovalau has been mentioned as an instance of this kind. The different interpretations that have been given to the lagoon floor at such reef breaches may now be considered. The lagoon floor, there unrimmed, appears to have been taken to represent a slightly aggraded platform, due to abrasion at normal ocean level in Wharton's and Agassiz' statement of the case, or at a lower level according to Daly's Glacial-control theory; or a platform of whatever origin, except that it must be antecedent to and independent of the existing reefs around the rest of the lagoon margin, as in Vaughan's interpretation. This observer, whose view will be here examined, appears to take unrimmed lagoon floors at reef breaches to prove that "the principal barrier reefs in the Pacific Ocean . . . are superposed on antecedent platforms that have been submerged in Recent geological time" (1919, p. 321).

But the unrimmed part of a lagoon floor may also be explained according to Darwin's theory as the open marginal arc of a surface, elsewhere reef-enclosed, which has been produced by long continued aggradation during slow, intermittent subsidence. Under this theory the unrimmed

part of the lagoon floor is supposed to have been kept free from reef growth by the outdrift of sediments, largely supplied by inwash over the windward reef flat. Thus the floor there has now, as it has supposedly had in the past, a depth of about 40 fathoms, because at that depth it is in adjustment to the waves and currents acting upon it. As long as inwash from the windward reef flat and outwash from the open arc of the lagoon floor continue, the leeward breach in the reef may be maintained; except that it may be slowly encroached upon by coral growth on the reef ends at either side. The lagoon floor may as persistently have its open margin built up to about 40 fathoms depth, provided that subsidence continues at a not too rapid rate. Thus explained, the even margin of the lagoon floor in a reef breach gives no indication whatever of the form or the depth of the rock foundation below it.

The Incomplete Barrier North of Ovalau

The breach in the barrier reef north of Ovalau is a typical example of its kind. The barrier-reef flat, as it swings around the southeastern side of Viti Levu and approaches Ovalau (Fig. 170), is nearly 2 miles wide for a distance of 8 miles; but it is narrower and somewhat discontinuous as it passes east of Ovalau, and it ends 4 miles north of that island, so that the lagoon floor there is open to the sea (Fig. 168). The lagoon behind the reef and between Ovalau and Viti Levu is 8 or 10 miles wide and from 15 to 30 fathoms deep. The inflow of sea water, driven over the broad barrier-reef flat on the southeast, must cause an almost continuous northward drift of the lagoon water; and, when the inflow is increased under strong winds and the lagoon waters are agitated by good-sized waves, the lagoon-floor sediments must be slowly drifted northward.

It seems inevitable that, under such conditions, the sediments must form an advancing or prograding embankment where the lagoon floor falls off to deep water and also that the edge of the embankment must lie at a depth of 30 or 40 fathoms, as is here the case. It is furthermore manifest that such a detrital embankment, like the narrow passes by which many reefs are interrupted, must be a very unfavorable situation for coral growth. It is significant to note that, just beyond the edge of the Ovalau embankment and therefore beyond the reach of drifting sediments, two small atolls rise from deep water to the sea surface. Although this explanation for the open margin of the lagoon floor by aggradation and progradation during subsidence has been strongly objected to, it still seems to me perfectly tenable. Whether the Ovalau lagoon floor has actually been formed in this way is, of course, still an open question.

The Breached Barrier Reef of Mbengha

Another example of a reef breach of the same kind as that north of Ovalau is found in association with the barrier reef around the island of Mbengha, next south of Viti Levu, HO 2858 (Fig. 171), the description

of which has been postponed to this section. Mbengha, 5 by 3 miles across and 1440 feet high, rises in the eastern part of its lagoon; it is described by Foye as consisting of a little-dissected, young volcano built on the ruins of an older one. A smaller island, a mile across, 450 feet high, rises in the western part of the lagoon; and two islets of volcanic rock rise in the inter-

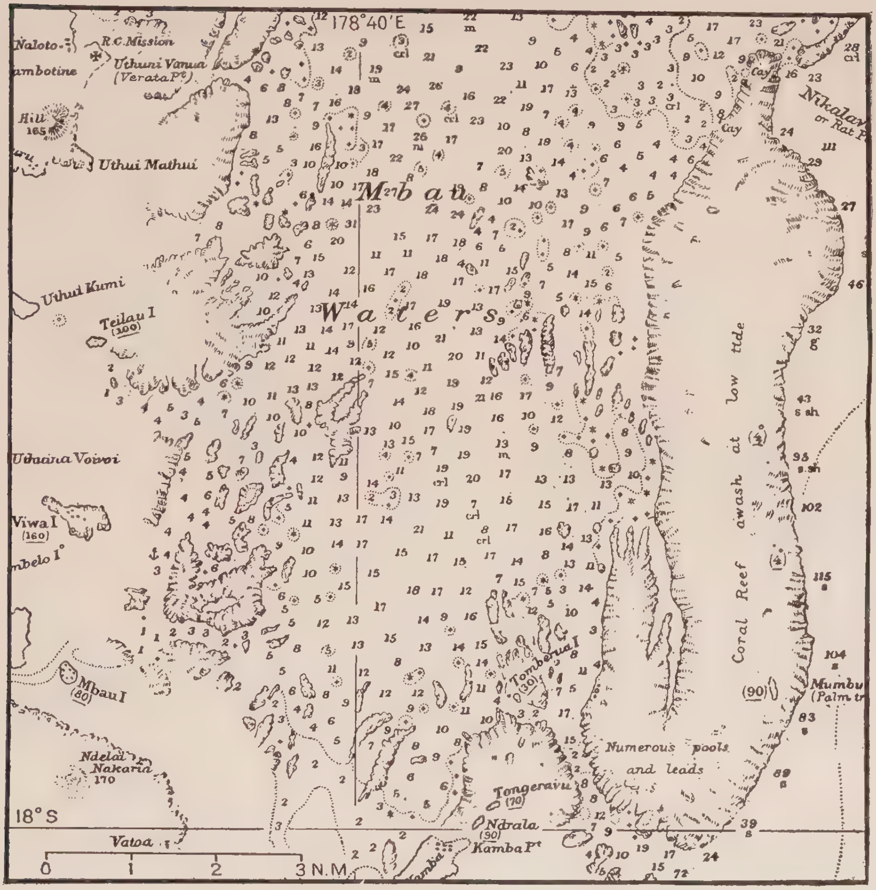


FIG. 170—Broad barrier reef flat, east of Viti Levu and south of Ovalau; HO 2859.

mediate space of 5 miles: hence the present lagoon probably represents a group of volcanoes, welded together. Both the larger islands have embayed shores. The encircling reef is of oval outline, with diameters of 16 and 9 miles; it is broad and continuous on the southeastern side, where the flat is from half a mile to a mile wide; it is interrupted by a number of passes on the northeast and the west; it is absent across a 4-mile breach on the north. The lagoon depth varies from 15 to 30 fathoms; a few small reef patches rise in the central area, and perhaps mark recently submerged islets. The depth increases to 40 or 50 fathoms in the breach, be-

yond which a rapid descent is made to the deep-water passage, with soundings of 150 fathoms more or less, which separates Mbengha and its reef from the southern barrier reef of Viti Levu.

Foye states that the Mbengha embayments "do not warrant the assumption that the [present] island has subsided to any great extent; certainly not enough to support the view that the subsidence of Mbengha

FIG. 171—Mbengha and its barrier reef; HO 2858.

has converted a former fringing reef into the present barrier reef" (1918, p. 81). In comment on this it may be urged that the steep fall of the Mbengha torrents on the younger volcano and the moderate amount of dissection that they have as yet accomplished make the occurrence of relatively short embayments (Fig. 172) in consequence of recent subsidence, perfectly consistent with a relatively strong measure of earlier subsidence by which the group of older volcanoes has been so largely submerged. The conversion of a large-island fringing reef into the present barrier reef, with the reduction of an original large island into two smaller ones in consequence of rather strong subsidence and the filling up of the smooth lagoon floor, seems to me in view of other Fiji reefs, highly probable.

The transportation of sediments across the Mbengha lagoon seems well assured. I had opportunity of walking and wading across the windward reef flat where it was nearly a mile wide and there saw thousands of reef

blocks up to 4 or 5 feet in diameter in various stages of disintegration; the flat was strewn with them as far as the eye could reach in either direction. A hammer stroke on 200 that I passed showed them to be limestone without exception. Small fragments abound. Although the wind was light, the surf was thundering on the outer face of the reef; and a drift of rising tide, fed by the surf in successive surges, was flowing slowly across the

FIG. 172—South coast of Mbengha, Fiji.

flat into the lagoon. At time of southeast storms, when the blocks are broken and lifted from the outer reef face, a large volume of water charged with detritus must sweep across the reef flat into the lagoon. The finer detritus must then drift across the lagoon floor, and some of it must pass out by the four-mile breach on the north.

As to the competence of waves to disturb the lagoon-floor sediments, it may be noted that, while I was skirting the northwest side of Mbengha in a cutter, a block of reef rock 12 or 15 feet in diameter was seen where it had been uplifted and perched upon the edge of a fringing-reef flat by the lagoon waves. The lagoon sediments must have been much agitated by waves that were strong enough to lift so large a reef block; and such waves, aided by the storm drift across the lagoon, must slowly shift the bottom sediments to leeward. The development and maintenance of a fairly well defined "edge" on the free leeward margin of a lagoon floor where a barrier reef is breached is therefore to be expected under the intermittent action of storm waves and currents.

Assumed Platforms Beneath Fiji Reefs

The brief allusion in the foregoing section to the possible occurrence of rock platforms beneath the barrier reefs of Fiji must here be expanded, for Vaughan has stated that certain reefs in Fiji and the Society group are superimposed on platforms antedating their presence (1914). This view doubtless holds good for the bank reefs in the Atlantic, where Vaughan first came upon it, but it is not satisfactory for the mid-Pacific reefs which fall off into deep water. The only semblance of a platform in connection with those stalwart reefs is seen in the unrimmed sectors of lagoon floors, just described, where the encircling reef is breached. But that unrimmed part of the floor as well as the rest has received an unknown thickness of detrital deposits while the barrier reef around the rest of the lagoon was forming. Hence it does not seem warranted to infer that a "platform"

underlies the whole lagoon merely because the unrimmed part has an even margin. The lagoon floor would be given such a margin by aggradation during subsidence, even if no platform underlay it, as has been shown above.

In confirmation of this conclusion against the presence of platforms under the reefs of Fiji, Foye's opinion regarding elevated Fiji reefs may be quoted: "As far as observed, the elevated limestones of Fiji rest unconformably on eroded volcanic rocks. They were deposited during the subsidence of eroded volcanic islands and are believed to have formed atolls and barrier reefs" (1918, p. 10). In none of the islands that Foye studied did he find a basal platform beneath an overlying mass of reef limestones; or more specifically he "was unable to discover in these islands any evidence of Pleistocene wave-cut platforms." On the contrary, it appeared to him "demonstrated that the older coralliferous limestones of Fiji"—that is the elevated reef limestones in the eastern part of the group, which best disclose the nature of their foundations and which will here be treated in a later chapter—"developed on a subsiding basement of [subaerially] eroded volcanic rocks, and formed barrier reefs and atolls" (1918, pp. 94, 95). In view of these results of the latest and most critical studies of Fiji reefs, it seems reasonable to look upon the reefs and lagoon floors now forming as controlled by conditions similar to those under which the earlier and now uplifted reefs were formed and to discard a view that is derived from the study of reefs in the marginal belt of the Atlantic. This aspect of the problem will be more fully presented in Chapter XV.

Summary for the Foregoing Smaller Islands of Fiji

The foregoing account of ten or more of the smaller barrier-reef islands of Fiji, all of which are situated in the central or southwestern part of the group and none of which bear elevated reef limestones, gives ground for the belief that they owe their barrier reefs to upgrowth during the slow subsidence of the reef foundations. It must be here remembered in the first place that the larger islands in the northwestern part of the group give independent geological evidence of their instability; and this will be supplemented in a later chapter by equally good evidence for instability from the many islands bearing uplifted reef limestones in the eastern part of the group. Hence the subsidence of the small islands above described is eminently possible. In the second place, all these islands, except Koro and Mbengha, have been maturely dissected; hence a great volume of detritus must have been discharged from them; and, in order that the discharge of so much detritus shall not have prevented the growth of encircling reefs, the islands must have subsided during the discharge, as has been more fully explained in the account of Moorea in the Society group.

In the third place, most of the islands are more or less embayed, just as they would be if they had subsided. It is true that, while the embayments of 30-mile Kandavu can hardly be explained without a strong sub-

sidence of that island, the embayments of certain smaller islands, such as Ovalau and Mbengha, are not large enough to demonstrate a great subsidence, because the valleys that they occupy are so short. However, the general form of so much of the maturely dissected islands as remains above sea level is such as to imply that, after suffering advanced erosion during a decidedly greater elevation than now, they suffered subsidence of a considerable amount. This is the more to be believed because low-level erosion during the Glacial epochs does not seem competent to account for the well opened slopes of the submerged valleys, let alone their inferred depth. In the fourth place, the distance at which the barrier reefs stand from several of the islands—especially Matuku, Totoya, Wakaya, and Ovalau—is most reasonably explained on the supposition tnat the reef base lies at a considerable depth on the submarine slope of the islands. There is no satisfactory reason for supposing that any shallower base has been provided for them. The subsidence of the islands is therefore regarded as well substantiated.

Nevertheless, in spite of subsidence, the reef-enclosed lagoons are of ordinary and fairly accordant depths. This should not occasion surprise, because the presence of the enclosing reefs gives assurance that whatever subsidence has taken place has not been faster than reef upgrowth. It therefore does not seem unreasonable to believe that lagoon aggradation during such subsidence has been competent to fill the "moats" between the island slopes and the reef walls. It should be here recalled that the absence of plunging cliffs on these Fiji islands, in contrast to the persistent presence of such cliffs on the marginal-belt islands of the Pacific and the Atlantic Oceans, suffices to exclude low-level abrasion from Fiji during the Glacial epochs and therefore to withdraw whatever aid that process might give to the production of accordant depths of lagoon floors. It may be added that, although several lowerings of the Glacial ocean undoubtedly took place, no consequences of such lowerings have been safely identified in Fiji. It should be remembered also that the long still-stand of the Fiji and other reef-encircled islands, which the Glacial-control theory assumes, does not rest upon any direct evidence but only on the supposed necessity of such still-stand in order that the postulated process of low-level abrasion shall produce the imagined rock platforms at a standard depth below the present lagoon floors. The absence of plunging cliffs behind the narrow fringing reefs of southwest Viti Levu, northeast Vanua Levu, and southeast Ngau descredits the occurrence of such abrasion. The smaller reef-encircled islands of Fiji are therefore accepted as witnesses against the Glacial-control theory and in favor of Darwin's theory.

Wallis, Northeast of Fiji

Wallis or Uea is a lonesome volcanic island northeast of Fiji, HO 2019, 11 by 5 miles, 630 feet high. Its slopes are of moderate declivity and, as

described by Viala, who spent four years there as resident physician (1919), are covered with a reddish clayey soil. Hence this volcanic island would seem to be farther advanced toward subaerial peneplanation than any other in the open Pacific. In spite of that, its shores do not appear to have plunging cliffs, as they should have if low-level abrasion had been operative upon them during the Glacial epochs. The shores are, on the contrary, of gradual descent and of moderate irregularity, bordered by

FIG. 173—Southwest coast of New Caledonia.

fringing reefs. A well-formed barrier reef, 17 by 10 miles over all, bears 16 reef-sand islets and encloses a lagoon 3 or 4 miles wide of unstated depth.

THE EMBAYED, REEF-FRONTED SOUTHWEST COAST OF NEW CALEDONIA

Physiographic Evolution of New Caledonia

The long, continental island of New Caledonia has already been given a general description in an earlier chapter in connection with the plunging cliffs and the barrier reef of its northeast coast. It will now be briefly referred to in connection with the barrier reef of its normally embayed southwest coast. An interpretation of its evolution by successive cycles of erosion and successive movements of depression has been briefly presented, in connection with the explanation of Figure 117, in the earlier chapter. The reef is believed to have grown up from the embayed, southwestern shore line of a down-flexed peneplain, the same peneplain, which, being upwarped in the present island, was cliffed along its northeast coast. The island area of the upwarped peneplain was exposed to erosion while the barrier reef was growing up offshore: thus, deep valleys were eroded in the hard-rock, mountainous area (Fig. 173), and rolling lowlands, now largely submerged in island-dotted bays (Fig. 174), were degraded in the weak-rock belts along the southwestern coast. This work demands, I believe, a much longer period of time than the sum of all the Glacial epochs. Hence renewed subsidence has given the coast the well embayed outline (Figs. 175, 176) that it has now gained by the entrance of arms of the sea into its valleys. Many illustrations of these features are given in my longer article on New Caledonia (1925 a). In consequence of this subsidence the southwestern barrier reef is believed to have grown up

to increased thickness and the lagoon to have gained increased width, especially where degraded lowlands bordered the island coast. The total measure of reef upgrowth may well be more than 1000 feet.

The southwestern barrier reef is now from 3 to 6 miles from the island shore; it is of vigorous form and fairly continuous, being interrupted by only 12 passes in a length of over 200 miles. Its junction with the northeastern reef is fairly well defined far to the northwest of the long main

FIG. 174—Embayed island in large embayment, southwest coast of New Caledonia.

island, but to the southeast no junction is effected; there the lagoon is not clearly separated from the ocean area even by charted soundings, much less by a reef wall.

Except in a middle stretch of several miles, where a recent emergence has raised a number of lagoon reefs above sea level and shoaled the lagoon floor, its waters have the ordinary depths of about 30 fathoms. The lagoon floor must therefore have been greatly aggraded during the upgrowth of the reef, if the above estimate of reef upgrowth is correct. The aggrading material must be supposed to come, as usual, from the reef by the overwash of storm waves, from the island by outwash of streams, and from organic sources in the lagoon itself. A boring in this great reef would be as instructive as the boring recently made in the Great Barrier Reef of Australia.

The embayments of the southwestern coast of New Caledonia are now much encroached upon by delta plains and mangrove swamps, but the headlands are little cut back by the lagoon waves. In so far as they are thus cut, the abraded wall and bench stand in sine-and-cosine relation to the slope of the headlands, as in Figure 177, thus implying that the last subsidence was relatively rapid. These narrow benches are, however, now somewhat emerged above the ordinary reach of the waves on the southwest as well as on the northeast coast; and I have wondered whether this was in consequence of Johnson's principle, to which reference was made in the account of the Fiji island of Ovalau, instead of in consequence of a eustatic lowering of ocean level, as Daly has suggested.

The Barrier Reef of New Caledonia

Thus interpreted, the barrier reef of New Caledonia may be regarded as one of the grandest exemplifications of Darwin's theory that the oceans afford. It is exceeded in length only by the still greater barrier reef of northeastern Australia, an account of which next follows. The formation

of both these mighty reefs is so closely associated with the embayment of the coast lines back of them that the theory of their having grown up during the slow subsidence of their foundations is thereby given good support. The support thus given is, indeed, better than that given by the association of certain other barrier reefs with the embayments of volcanic

FIG. 175—Nouméa Peninsula, New Caledonia.

islands, because the continental rocks of New Caledonia and Australia have demonstrably lost so much of their former area by the subsidence which caused their embayment. But while this support has been recognized by several Australian students of their great reef, it has not been recognized by any of the French students of the New Caledonian reef.

Chambeyron, who has given the most detailed account of this reef, treated it chiefly from a navigator's point of view. Most of the French geologists who have visited their long island were so absorbed with the study of its nickel ores that the barrier reef received little or no attention from them. Bernard, who has prepared an excellent general account of

the island based on all available material, does not seem to have recognized that the coastal embayments demonstrate subsidence, and he explicitly discredits Darwin's theory; he does not deny subsidence but finds no reason for thinking that it has taken place. Instead, he accepts Suess's views as to a lowering of ocean level in explanation of the emergence of the Loyalty Islands, three good-sized atolls not far northeast of

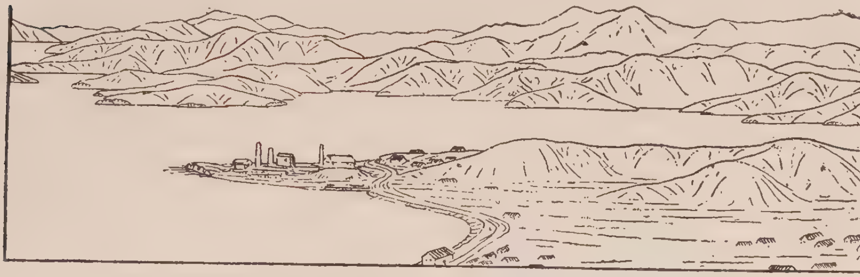


FIG. 176—View of Ducos Peninsula, as seen from a hill on Nouméa Peninsula.

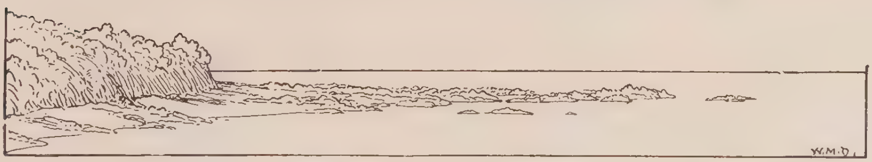


FIG. 177—Low bluff and broad bench at spur end; southwest coast of New Caledonia.

New Caledonia to be described in Chapter XVI of this volume, without noting that such a lowering of the ocean would have required an equal emergence of New Caledonia and its reefs, of all other islands and reefs, and of all continental coasts as well, unless they sank by the same amount at the same time. He compares the lagoon floor inside the New Caledonian barrier to the continental shelf of the coasts outside of the coral seas and concludes: "Les eaux ont nivelé la surface d'abrasion et denudation marine sur laquelle se sont installés les coraux" (1895, p. 40). In this conclusion I believe he was unconsciously correct for the northeastern barrier, where, unknown to him, the presence of the plunging cliffs testifies to abrasion; but he was altogether incorrect for the southwestern barrier, where the absence of shore cliffs testifies to the absence of abrasion.

For both coasts of New Caledonia, one formerly abraded, the other not, the opportunity for reef upgrowth of which such wonderful advantage has been taken may be confidently ascribed to island subsidence, good evidence for which is found in the shore-line embayments, quite independently of the reef upgrowth which it promoted. Nevertheless, the enclosed lagoon floors, one believed to have an abraded platform at a considerable depth beneath it, the other thought to be underlain by a more or less dissected and downwarped area of the former New Caledonian pene-

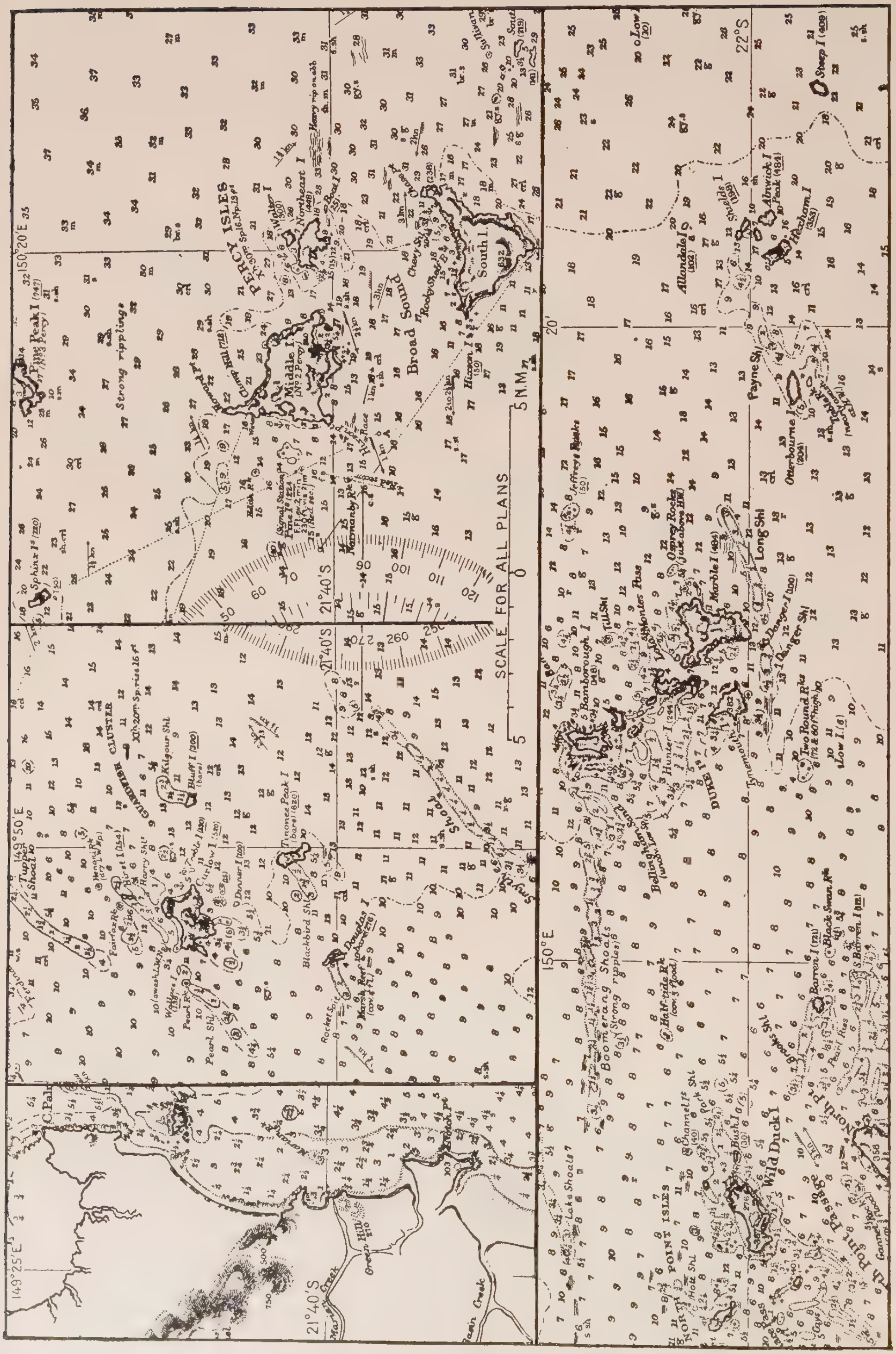


FIG. 178—Islands off the Queensland coast of Australia; HO 3454. The lower excerpt is 7 miles south of the upper three.

plain, are of normal and similar depths; and they are both included in Daly's lagoon-depth tables (1915), which are said to "indicate that the new [Glacial-control] theory withstands a statistical test, which is as plainly damaging to the subsidence theory."

The Great Barrier Reef of Australia

General Features of the Reef and of the Protected Coast Behind It

The greatest of all barrier reefs fronts the Queensland coast of north-eastern Australia, HO 3452–3463, for over 1000 miles and encloses a lagoon of ordinary depth, usually from 20 to 40 fathoms, but of the extraordinary breadth of from 20 to 70 miles. The mainland coast behind the reef is for the most part of fairly strong relief, and it would be well embayed if it were not that the bays produced by a recent submergence have now been largely filled with alluvial plains. The headlands between the bays do not show strong cliffs, but bench-based walls or bluffs are cut in their slopes at present sea level. Many large or small, mountainous or hilly islands rise from the lagoon waters, the smaller ones predominating off-shore (Fig. 178), and only the larger ones being well embayed (Figs. 179 and 180). Their sheltered landward sides slope gently below the water line; their exposed seaward sides are, like the headlands of the main, cut back in bluffs which may rise as high as 50 feet; but, as the bench at the bluff base lies at present sea level, both bench and bluff must be ascribed to the recent work of the lagoon waves. In view of the great breadth of the lagoon and the strength of its waves when gales are blowing, the bluffs are expectable features.

Among the accounts of the Great Barrier Reef and its associated features is an early one by Captain Cook, who told of the many lagoon islands (1884, Vol. 3, p. 537). Later ones are by Flinders, who explored many reefs and bays (1814); Jukes, whose account of the surf on the reef front has been quoted in Chapter I; and Huxley, who as assistant surgeon on the British surveying ship *Rattlesnake* in 1849, wrote of the "parlous dull business" he found his duties there (1901, Vol. 1, p. 47). Several other authors are referred to below. Near the northern end of the reef it is resolved into discontinuous patches, a few of which constitute fringes around volcanic islands of moderate height. The best known of these is Murray Island, which has been well described by Haddon, Sollas, and Cole (1892–96) and for which the ecology of the corals has been minutely studied by Mayor (1918). Farther south is Bramble Key, in the center of which is a volcanic knob, 60 feet across and 20 or 30 feet high; this is very probably the partly submerged remnant of an originally higher mass. These volcanic islands and islets appear to be of more recent origin than the reef-fringed old-rock islands farther west, between Cape York and New Guinea, the subsidence of which seems unquestionable for reasons quite apart from reef upgrowth.

FIG. 179—Embayed islands off the Queensland coast of Australia; BA 347.

The enclosing barrier reef is often developed in great strength, some of its flats having a width of a mile. Kent's photographic views of the reef (1893), showing vast fields of growing corals at low tide, are of admirable excellence. A committee for the study of the reef has recently been organized in Australia, with Charles Hedley as its scientific director, and a boring in the reef has been made. My own acquaintance with the Great Barrier is limited to a steamer trip in the lagoon northward to Cairns, near

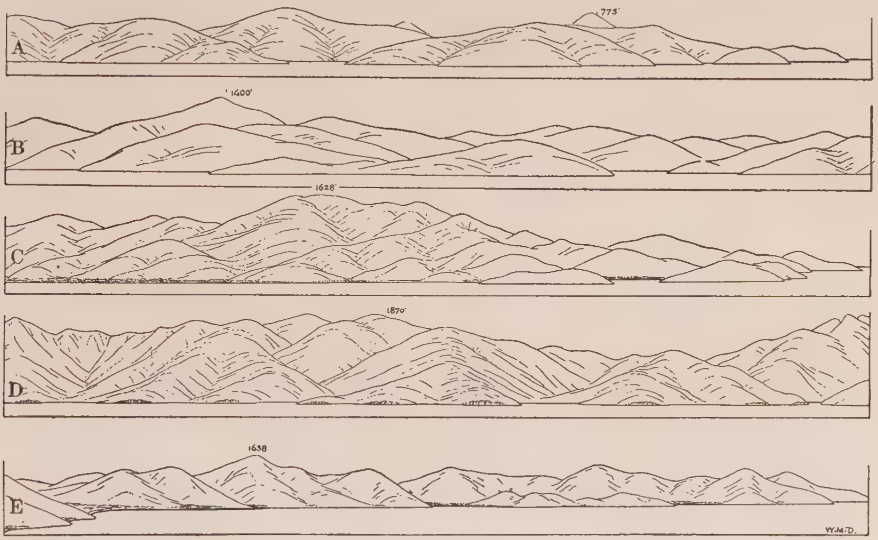


FIG. 180—Views of the islands shown in Fig. 179.

the lagoon mid-length, and back: my attention was given chiefly to the features of the coast. An overnight stop on one of the reef islands off Cairns was an entertaining experience but, as might have been expected, entirely fruitless as far as the origin of the reef is concerned. A discussion of the results of my observation has been published in a special article (1917b).

Opinions of Earlier Observers

Many opinions have been expressed as to the origin of the Great Barrier. Jukes, the first geologist to study it (1847), regarded it as exemplifying Darwin's theory of upgrowth on a subsiding foundation, as in section *A*, Figure 181. This early opinion seems to be supported by Hedley, one of the latest and most competent students of the reef, who states: "There is a general agreement that large and long-continued depression has prevailed in the Barrier Reef region" (1926, p. 189).

On the other hand, Gardiner, the most experienced English student of coral reefs today, has said that the theory of subsidence is here "absolutely excluded" and that it must be replaced by the theory of veneering

reefs on sea-cut platforms (1898). Unfortunately this opinion was reached without consideration of the evidence against abrasion that is so clearly afforded by the absence of strong coastal cliffs on the islands and mainland of the reef-protected Queensland coast, although such cliffs characterize the exposed Australian coast south of the reef as will be further told below, and without consideration of the evidence for submergence, probably due to subsidence, that is as clearly afforded by the embayments of the coast, to which Penck in far-off Vienna first drew attention (1896). Gardiner even asserted that "the coast of Australia inside the Great Barrier Reef certainly does not show the characters that Dana propounded" (1898, p. 489); but this is clearly an error.

Agassiz made an extended examination of the Great Barrier, but there as elsewhere explained what he saw of the coast much less by the submergence of an eroded land surface than by inroads of the sea. He concluded that "there is no proof of any extensive subsidence since the Cretaceous period" and that the reef is "only a veneer of at most twenty fathoms upon the faces of the denuded platform of the islands which once formed the outer line of the Australian continent" (1898). No evidence for the existence of such a platform is forthcoming.

Much light on the post-Cretaceous history of the eastern margin of Australia, which has been by no means so quiet as Agassiz supposed, was shed shortly after his visit by the physiographic interpretation of a central district, known as New England, by E. C. Andrews, who showed that subsidence has recently taken place offshore while uplift was in progress in the coastal highlands. In a word, he showed that the coastal belt has been flexed and that "the effect of the late subsidence was . . . to give birth to the Great Barrier reef" (1900–04, pp. 214, 215). Andrews' statement was soon extended by Hedley and Taylor, who instanced a certain well-embayed, medial part of the coast with outlying islands as "a characteristic product of subsidence; . . . its features could not be evolved by erosion and denudation. . . . Marine erosion seems to us to play a paltry part in the moulding of the Queensland coast, the main features of which we ascribe to subsidence" (1907) after well advanced erosion.

Daly asserts: "The entire area now occupied . . . by the great barrier reefs of Australia and New Caledonia was, during the maximum of Pleistocene glaciation, bereft of reefs growing rapidly enough to resist destruction by the waves"; but he adds: "There is no necessity of believing that the entire shelf [of the Queensland coast] . . . was formed by Pleistocene wave-benching" (1915, pp. 169, 198). Vaughan argues that the Great Barrier Reef is an upgrowth from a platform of independent origin and of recent and small submergence, as in section *B*, Figure 181, and adds that the platform "was a land surface in Pleistocene time." He concludes: "The idea that the platform was formed by infilling behind the reef may be permanently set aside" (1916, p. 45). My own opinion is that the total

submergence of the Queensland border since reefs began to grow there and the total thickness of reef upgrowth from the foundation thus offered on the submerged land border, as well as the total thickness of lagoon deposits now included between the downslope of the submerged land and the

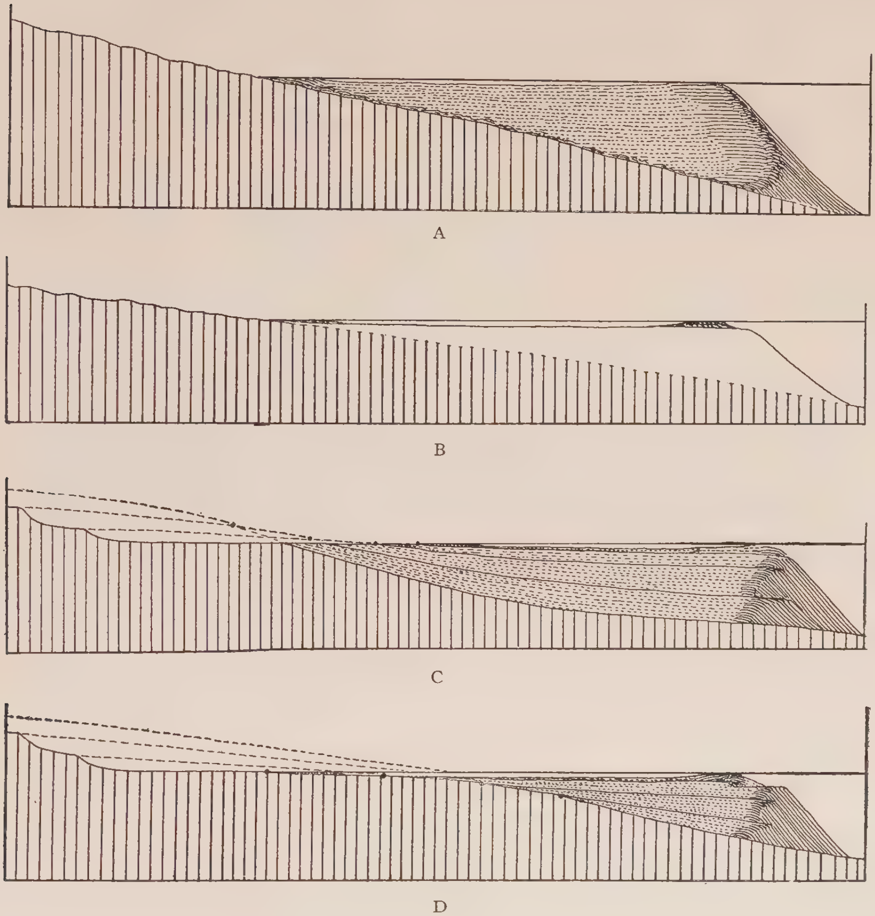


FIG. 181—The Great Barrier Reef of Australia, according to Darwin, section A, and others, section B. The two lowermost sections illustrate the shifting of axis of flexure, Queensland coast.

inner face of the barrier reef, are all of large measure: in other words, that this reef is as good a witness for Darwin's theory as Jukes took it to be.

Physiographic Development of the Coast

It may well be true that the last depression of the lagoon area was of small amount, that the upgrowth of the reef since that depression is of small measure, and that the thickness of lagoon sediments deposited since the depression is also small. But it appears also to be true that the last depression was preceded by an earlier depression of greater measure; and

hence it is probably true that the latest upgrowth of the reef was preceded by earlier upgrowth. There can be, in any case, no question that the present eastern border of Australia has greatly retreated from the former eastward extent of that continent and that part of the former extent now lies beneath a deep sea. David's views on this matter are here pertinent. After calling attention to the nearness of the height of land to the eastern coast of Australia, he wrote: "This extraordinary position of the Main Divide taken in conjunction with the evidence of waterfalls like the Barron Falls, 800 feet high [on an east-flowing river], and the numerous high granite and slate islands [in the lagoon of the Great Barrier] is almost certainly due to comparatively recent crust foundering on a grand scale along the region of the Great Barrier Reef, whereby almost the whole of the eastern side of the old Divide has been let down below sea-level. Thus only a few miles of the heads of the eastern rivers have been preserved. As the result of this extreme betrunking they have become greatly overhung above the foundered area. Hence the steep-to coast and high waterfalls" (1911, pp. 41–42). A profile with exaggerated vertical scale accompanies this statement and shows strong downfaulting on several imagined fractures under the lagoon; a true-scale profile would show flexure to be more probably responsible for the foundering of the former land area than faulting, although certain north-northeast alignments of the Queensland coast have been taken to indicate that oblique faulting has had a share in depressing the continental margin.

Moreover, it is eminently possible, as Andrews suggested, that reef growth may have taken place, more or less intermittently, during the progress of that great foundering. The effort will therefore now be made, following the scheme of coastal development that Andrews has presented but carrying it farther than he did with respect to the submerged belt, to trace the possible succession of early-formed reefs into the present reef. For it is evident that, if, in a late stage of such a succession, a maturely broadened reef with a delta-filled lagoon behind it were formed during a still-stand pause in the general depression of the coast, such a reef-and-lagoon plain might very well serve as a platform up from which the present reef could grow when depression was renewed.

The coastal highlands of the New England district, of which I had a partial view by rail, are described in Andrews' essays as rising in three successive benches—here to be called stories—over a ground floor of the coastal lowlands. The three stories are explained as related to three cycles of erosion separated by movements of elevation, as summarized in Figure 182; the uppermost story of today being of earliest production. The deformed structure of the region indicates that it once had a mountainous form, as in the background block, *A*. Those mountains were worn down to a peneplain, *FF*, in the second block; and it is this peneplain, successively uplifted and eroded but still in part surviving in rolling highlands some distance inland, that now

constitutes the third or uppermost story of the coastal belt. The sequence of changes is supposed to be about as follows: The earliest uplift of the first-formed peneplain, which introduced the first of the three cycles of erosion here to be more particularly considered, gave rise to a slanting upland, *GG′*, block 1. Associated with this slanting uplift of the land there was a slanting depression of the adjacent sea floor. The total

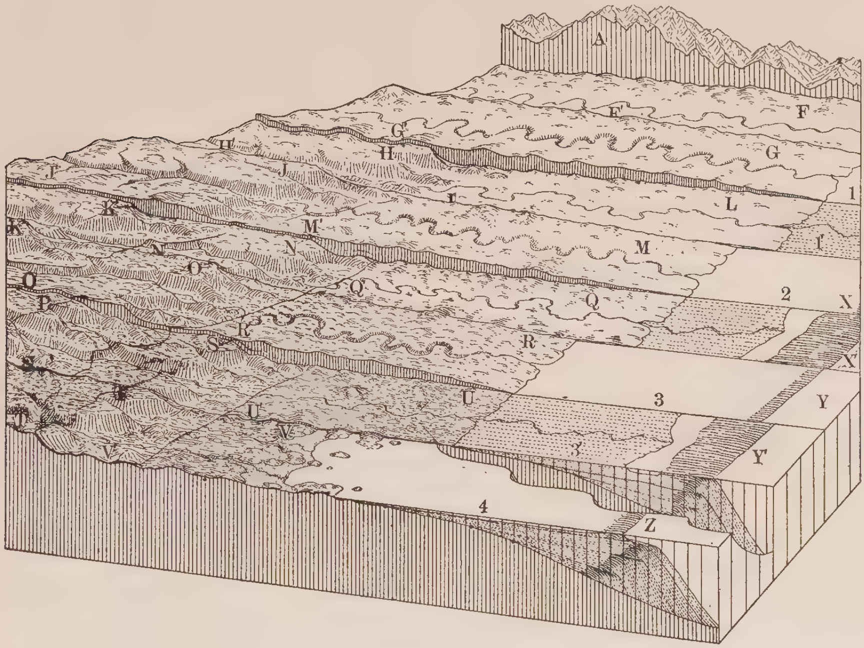


FIG. 182—Block diagrams illustrating the development of the Queensland coast.

movement may be conceived as a flexure, or "tectonic rocking" as Hedley and Taylor call it (1907, p. 409), between the interior continental area to the west and the deep ocean area to the east. After the upflexure the coastal part of the slanting upland was worn down to a second peneplain, *LL′*, block 1′, while the interior part, although dissected by valleys, still retained much of its height of uplift, *HH′*.

This process was twice repeated, as in blocks 2, 2′, and 3, 3′. By no simpler scheme does it seem possible to account for the actual features of the New England district; namely, a coastal peneplain, *UU′*, block 3′, surmounted by residual hills and backed in the interior by the three-story highlands, two of which, *S* and *P*, are shown in block 3′; the third is omitted for lack of space. The lowest and latest-formed peneplain has recently been more or less submerged along its margin, probably by a gentle tilting, as in block 4; and a slight emergence of still later date has raised discontinuous littoral strips of marine deposits to a small height above sea level. In evidence of the gentle tilting of the latest peneplain

just mentioned, it may be noted that its streams are incising narrow valleys of small depth in its rolling lowlands as they approach the embayed shore; this could not be the case if a uniform depression had taken place. Furthermore, while the residual mounts on the non-submerged part of the coastal lowlands exhibit their long concave lower slopes as well as their convex higher slopes, the small islands not far offshore, which undoubtedly represent similar mounts on submerged parts of the lowland, exhibit only their convex higher slopes; and this also strongly suggests a gentle tilting.

Care should be taken not to apply Andrews' scheme for the development of the New England district too literally in the interpretation of the Queensland barrier reef. His field of investigation lay, as has already been noted, in northern New South Wales and therefore to the south of the Queensland coast which the reef fronts. It has not yet been shown that the three-story features which characterize the first of the two districts extend into the second. Hence neither the upflexing of the Queensland border, now a dissected highland, nor the downflexing of its former eastward extension, now an aggraded sea bottom, should be patterned too closely on the three-cycle scheme of Figure 182. Nevertheless, that figure combines the development of the New England coastal highlands with the upgrowth of the Queensland barrier reef; and, although the combination very likely errs in certain respects, it is believed to be essentially correct in exhibiting the manner in which successive downflexures of the sea floor, whatever their number and measure may have been, would cause corresponding upgrowths of the barrier reef.

The flexures probably included many small impulses, and the upflexing of the highland belt must have been rapid enough to raise the inner part of the first-formed peneplain much faster than it was worn down; yet the associated downflexing of the sea floor need not have been faster than reef upgrowth. It is essential, however, that in the New England district at least the brief periods of more active movement should have been separated by much longer periods of rest; otherwise the several peneplains of that district could not have been developed so well as they have been.

Correlation of Coastal Development and Reef Upgrowth

Certain extensions of Andrews' physiographic scheme may now be ventured upon. The axis on which the coastal region was upflexed on the land side and downflexed on the ocean side can hardly have remained fixed; for, during the long continued reduction of greater ancient Australia to its smaller modern dimensions, a fixed axis of flexure is altogether improbable. The axis cannot have migrated seaward, section *C*, Figure 181, because such a migration would have exposed abundant marine deposits on the coastal lowlands; and such deposits are almost absent. The axis therefore presumably migrated landward, thus causing a progressive and embaying encroachment of the sea, as in section *D*, Figure 181. It is in association with the progressive downflexing of the sea floor, thus condi-

tioned, that reef upgrowth is conceived to have been promoted. It is furthermore eminently possible that the reef may have been approached, if not reached and smothered by outgrowing and lagoon-filling delta plains during the long still-stands in the later stages of each cycle of erosion that the region has experienced, as shown in blocks 1′, 2′, 3′, Figure 182.

Even in the present early stage of the recently introduced cycle, the aggradation of the lagoon is well begun. Agassiz wrote: "We found the water of the inner channel [lagoon] of the Barrier reef comparatively muddy, considerable silt being held in suspension. . . . The fine mud and silt which everywhere cover the bottom of the inner channels of the Barrier reef indicates only too clearly where the telluric material has been swept to. In fact, this extends generally over the bottom" (1898, pp. 107, 109, 110). It is therefore eminently possible that, during prolonged still-stands, such as must have been necessary to wear down the coastal uplands to lowlands, an encroachment of delta plains upon the barrier reef, as above suggested, actually took place. The manner in which the young and narrow reef *Y* of block 3 (Fig. 182), comes to be, in its broader form *Y′* of block 3′, threatened with burial calls for special consideration; for near its southern end the advancing detritus appears to have been furnished not only by the outward growth of mainland river deltas but also by the northward growth of sand reefs from the non-reef-fronted coast farther south. A digression must here be made regarding these sand reefs.

The Invasion of the Great Barrier Reef by Sand Reefs

The eastern coast of Australia offers today, as already noted in the account of the South Pacific marginal belt, the interesting spectacle of the invasion of the southern end of its coral- or barrier-reef area by long, littoral sand reefs. The form of the sand reefs, evidently the product of wave and current action since the present attitude of the land was assumed, suggests that they are growing northward under the action of a local, north-flowing current, the presence of which is confirmed by Halligan, Hydrographic Officer for New South Wales (1906, p. 634). The long, north-growing sand reefs are the correlatives of many others of less length, farther south (Fig. 183), which span the mouths of drowned-valley embayments in curves concave seaward, somewhat back of the cliffed headlands on either side of the bays, or which not infrequently tie islands to the mainland.

The first of the northern sand reefs, about 50 miles long, Figure 184, is separated from the mainland by a tidal channel on the south and is divided by another tidal channel near its middle into two stretches, known as Stradbroke and Moreton islands, both concave seaward and both apparently reaching to rocky islets at their northern ends. They enclose Moreton Bay, 15 miles wide, back of which Brisbane, the capital of Queensland, is situated on the coastal lowland. The second sand reef, farther north, is over 70 miles long and consists of three unequal stretches, each

concave seaward and each again seeming to reach northward to a rocky islet. The second and third stretches, known as Frazer or Great Sandy Island, are separated from the first by a tidal channel; and the northernmost, which ends 45 miles offshore, is continued by a shallow sand bar, known as Break Sea Spit, about ten miles in length. Hedley calls attention to an extraordinary increase in sea-bottom depth five or ten miles north of this spit, between surveys of 1868 and 1904 (1911), from which it may be inferred that the advance of the spit has caused an energetic scouring of the sea floor beyond it.

Fig. 183—Headlands and beaches, Queensland coast; north of Fig. 184, HO 3454.

Now it is significant that the present boundary between the northern end of Break Sea Spit and the southern end of the barrier reef lies between latitude 23° and 24° S. and that this boundary is almost 400 miles nearer the equator than the present limit of coral-reef growth in Australian waters as marked by the Elizabeth and Middleton bank atolls, already described in the account of the marginal belt of the South Pacific as standing not far off the Australian coast in latitudes 29° and 30° S. Richards and Hedley note that "conditions are really becoming very adverse for coral reef formation" at the south end of the barrier (1925, p. 25). Hence the Great Barrier must have formerly extended south of its present end. Agassiz gave a vivid account of the facts of the case. "It is a curious coincidence," he wrote, "that at Break Sea spit, as well as at Cape Florida [in the United States], we should find the encroachment of the siliceous sands, in one case coming from the north along the coast of Florida, and in the other coming from the south along the shore of Frazer island, gradually preventing the farther northern and southern extension of coral reefs in the two regions. . . . From the character of the soundings upon the bank, indicating the former extension of Break Sea spit, it is evident that the corals upon the spit are dead, and that they have probably been killed by the encroachment of the siliceous sands creeping northward on the surface of the spit" (1898, pp. 104, 105). This is truly an extraordinary correspondence between Florida and Queensland, and all the more so when it is noted that the currents concerned appear to be backset eddies driven by offshore currents.

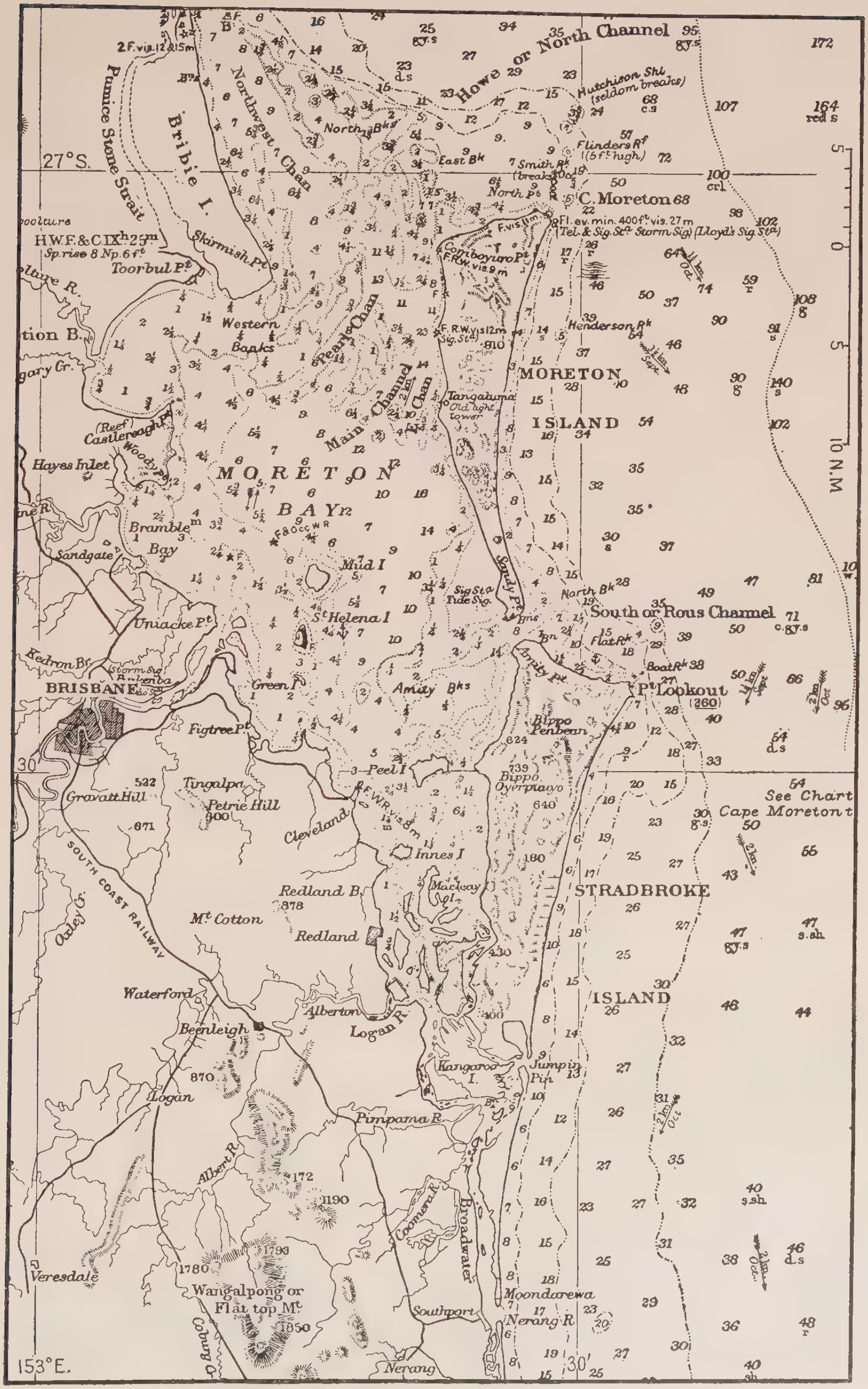


FIG. 184—Sand reefs, Queensland coast, south of Great Barrier Reef; HO 3429.

The Frontal Bank Below the Southern Reef

We may now return to the topic that was under discussion before this digression about the sand reefs was entered upon; namely, the conditions of barrier-reef growth at the close of the cycle of erosion that preceded the current cycle, as represented in block 3′, Figure 182. Evidently a strongly unfavorable influence must have been exerted by the north-growing sand reefs upon the barrier reef of that time. For in consequence of sand-reef growth in the early youth of the present cycle, the barrier reef has already lost several score miles of the length with which it presumably began the cycle; hence it may have been overwhelmed with sand for several hundred miles of its proper southern length during the late stages of the preceding and long-enduring cycle, when the sand reefs had had plenty of still-stand time for their northward growth. And, when thus overwhelmed, the dead barrier reef with the overwhelming sands upon it must have been cut back by the sea, which had been powerless to consume it so long as its corals were alive.

We should have then had in this southern district of the Great Barrier an actual example of an overwhelmed and cut-back coral reef, such as is drawn for an ideal case in sector *K* of Figure 53; but instead of this Australian reef having been overwhelmed only by delta growth, as in the ideal figure, it was probably overwhelmed chiefly by sand-reef growth. The reason for this inference is that sand-reef growth in the current cycle has been much more rapid than delta growth. Consequently the Great Barrier farther north, where it was threatened only by advancing deltas, may have escaped being overwhelmed and abraded. When a moderate subsidence closed the preceding cycle and introduced the current cycle, the new coral reef may well have been superposed on the earlier coral reef through the major part of the Great Barrier; but in the southern part, where the earlier coral reef had been overwhelmed by sand reefs and where retrogressive abrasion had occurred, the new uppermost reef may have grown up from the cut-back edge of the previous reef, as in section *D*, Figure 181.

Thus the singular back-standing position of the Great Barrier with respect to the out-standing margin of the bank in front of it, to which Vaughan has called attention and which is found chiefly in its southern part, may perhaps receive an equally singular explanation. If parts of the Great Barrier farther north also occupy a back-standing position, that may mean that the underlying reef was there cut back because it had been locally overwhelmed by delta growth. As far as the barrier reefs of the Pacific coral seas are concerned, the back-standing position of the Great Barrier is as exceptional as the explanation here proposed for it. A corollary of this explanation—which, be it noted, may apply to earlier cycles of reef upgrowth as well as to the two latest ones—is that a

boring through the present reef may encounter detrital deposits at a depth much less than that of the lowest reef foundation.*

The foregoing extension of Andrews' physiographic scheme for the development of the New England coastal district is not one upon which I should care to insist closely; it involves too many inferences to be fully trusted. On the other hand, it is not merely an offhand suggestion, for it takes account of two factors not previously introduced into the Great Barrier problem and yet surely deserving of consideration there. One of these factors is the long still-stand in the later stages of the third cycle of erosion when the coastal lowlands were worn down to low relief, before they were more or less submerged by a recent and gentle eastward tilting; this tilting presumably being the latest manifestation of the long continued flexing by which the highlands have been raised on the west and the sea floor depressed on the east. The other factor is the great northward growth of the sand reefs which presumably took place during that long still-stand before the latest eastward tilting, and in consequence of which a correspondingly long stretch of the Great Barrier must then have been overwhelmed. The verity of the first factor is based upon the small relief of the coastal lowlands as they are seen in certain stretches back of the Great Barrier. The verity of the second factor is based upon the observed dimensions of the north-growing sand reefs of the present cycle.

The Great Barrier Reef and the East-Australian Continental Shelf

Another aspect of the Great Barrier problem remains to be considered. Several writers, among whom are Guppy (1890, pp. 60, 67), Forbes (1893, p. 543), Andrews (1902, p. 177), Hedley and Taylor (1907), Vaughan (1914, 1916, 1916b) and Lenox-Conyngham (1925), have noted that the lagoon floor back of the Great Barrier along the Queensland coast is apparently continued southward in the well-formed continental shelf that fronts the New South Wales coast beyond the end of the Barrier and have therefore inferred that the reef has grown up only from a former northward extension of the same continental shelf. In this connection Vaughan concludes: "The submergence of the Australian continental shelf apparently can be assigned to recent rise of sea level because of deglaciation, as it seems that most of the surface of the platform was exposed as a dry land area by withdrawal of water from the ocean during at least a part of Pleistocene time" (1919, p. 321). This implies that

* Since the above statement was written, David has briefly announced that the boring in the Great Barrier has penetrated 427 feet of coral material, mostly detrital, and 173 feet of quartz sand probably deposited "in shallow water" (1927, p. vii). As the total depth of this boring is small compared with the probable depth of the rock foundation below the reef, it seems probable that the quartz sand represents a reef-burying delta plain formed by outwash from the mainland or a reef-smothering sand bar formed by longshore currents, during the still-stand that permitted the erosion of the latest peneplain or ground-floor lowland, and hence that reef or lagoon limestones may be found below the quartz sand if the boring is continued to greater depths.

the upgrowth of the Great Barrier reef has accompanied or followed the Interglacial or Postglacial rising of the ocean level. An emergence, more or less complete, of the lagoon floor to the north and of the continental shelf to the south presumably took place when the ocean was lowered in the several Glacial epochs; but the now embayed valleys of the coast are so wide that it is impossible to believe they were excavated only during those epochs of ocean lowering: hence land subsidence as well as ocean rise must be here recognized.

In illustration of the measure of acceptance of the above-indicated correlation of the northern lagoon floor and the southern continental shelf of eastern Australia, the following extract may be made from R. T. Chamberlin's report on the reefs of Tutuila, already cited in the account of that island: "In 1902, E. C. Andrews showed that the foundation on which the Great Barrier Reef of Australia rests does not come to an end with the southern limit of the coralline mass, but continues southward as a submerged platform into the cooler seas, from which he inferred that only a part of the whole structure is formed of coral growth. The coral reefs are perched upon a flat shelf resulting apparently from marine planation in part, and in part from the submergence of a coastal plain" (1924, p. 151). To my reading the first sentence of this quotation overstates Andrews' results; and the last sentence goes altogether too far in presenting the results as demonstrated conclusions. Indeed, no compelling reasons are given by Andrews for believing that the organic barrier off the Queensland coast is based upon an inorganic detrital shelf. Belief in its origin on such a base seems to be grounded rather on an offhand suggestion than on a critical investigation.

Continental Shelves as Foundations for Barrier Reefs

It seems to have been tacitly assumed by the above-named writers that coral reefs were wanting along the whole of the east coast of Australia during the long period in which the former eastward extension of the continent was depressed and the present continental shelf was built up upon the submerged slope. They seem further to have assumed that, when the shelf had essentially reached its present form, a strong reef was established along or near its outer margin off the Queensland coast. But no reason has been given either for the long delay in reef establishment or for the establishment of a reef after the long delay; nor have other continental shelves been examined to learn whether fitting conditions for reef establishment were offered on such shelves or not. Such an examination, here undertaken in Chapter IX, leads to the belief that continental shelves are in general not well fitted for the upgrowth of reefs. The absence of a well developed barrier reef around the margin of the continental shelf known as the Sahul Bank north of Australia seems particularly significant in the present connection: some atolls, perhaps marking submerged islands, have grown up from within the area

of the bank, but no barrier reef rises from its margin. Indeed, the only case in which a barrier reef elsewhere rises from the margin of a continental shelf is along the eastern side of the great Sunda Bank, southeast of Borneo; and there the reef is very imperfectly developed, as will be told in a later section of this chapter. That the greatest barrier reef of the world should have grown up off the Queensland coast from a foundation of a kind that is elsewhere found to be so poorly fitted for reef upgrowth should not be believed without good evidence.

On the other hand, a great barrier reef, second only to that of Australia, rises off the southwest coast of New Caledonia, which is believed to have been downflexed. If a similar downflexure has taken place along the Queensland coast, a great barrier reef might have grown up there also, even if, at the same time, an inorganic continental shelf were built up in the cooler water along the similarly downflexed coast of New South Wales. The chief difference between the two reef-fronted coasts here compared is that the southwest coast of New Caledonia has a relatively small land area behind it; while the east coast of Queensland has a larger land area behind it. But if the breadth of the land area that is drained to the two coasts is compared, the difference will not be found very great. The subsidence theory therefore appears to me to offer a better opportunity for the establishment of a barrier reef off the Queensland coast than does the continental-shelf theory.

The Coastal Features of Queensland and New South Wales

The consequences of the two theories with respect to the coastal features today expectable back of the Great Barrier Reef remain to be deduced. This may easily be done. A non-reef-protected continental coast not built forward by the deltas of large rivers from high mountains, and therefore continuously exposed to wave attack while a continental shelf is developing during the progressive downflexure of the adjoining sea floor, should have its outlying islands destroyed by abrasion, and its near-shore islands as well as its headlands should be cut back in strong cliffs. The cliffs would plunge below sea level if a recent downflexing had taken place since the cliffs were cut, as is believed to have been the case along the northeast coast of New Caledonia. On the other hand a continental coast, offshore from which a barrier reef is continuously growing up during the downflexing of the adjoining sea floor, should have an abundance of smaller offshore islands and of larger and smaller near-shore islands; and except for low bluffs cut by lagoon waves, both islands and mainland should be free from cliffs.

When these two sets of strongly contrasted consequences deduced from the two rival theories are confronted with the actual features of the Queensland coast, there cannot be a moment's hesitation in deciding which set of consequences is supported by the facts and therefore which one of the two theories should be adopted in explanation of the Great Barrier Reef. The

embayed coast of Queensland has abundant offshore and near-shore islands (Figs. 178, 179), which are without strong cliffs, although lagoon-wave bluffs and benches are developed in moderate strength; and these features are precisely those expectable under the subsidence theory. That theory is therefore supported by the coastal features, and the other theory is contradicted.

Be it noted further that, although the deduced features of the continental-shelf theory are strongly contradicted by the actual features of the Queensland coast, they are as strongly confirmed by the actual features of the New South Wales coast, where islands are rare and cliffs are strong, as told below. This confirmation gives excellent warrant for believing that, if the continental-shelf theory were correct, the coastal features deduced from it would be found along the entire eastern coast of Australia, instead of only along its southern half.

The contrast between the northern and southern stretches of the coast, as presented in Figures 178 and 179 for the northern and in Figure 185 for the southern half, are therefore most illuminating. Both stretches have embayed shore lines, because both stretches have taken part in the down-flexing by which ancient Australia has been reduced to its modern dimensions. One of the best embayments, that of the drowned valley of Hawksbury River, is well shown in one of Andrews' papers (1903, Pl. 42). But outlying islands are practically unknown in the south, although occasional small shoals may represent their abraded stumps, as in Stanfield Bay (Fig. 185). Near-shore islands of good size are not uncommon; they are usually tied to the mainland by sand reefs, as next north of Port Jackson and next south of Botany Bay in Figure 185. These good-sized, near-shore islands, taken with the drowned-valley embayments, which are often of elaborate pattern, show that smaller offshore islands also would be present as a consequence of the down-flexing of the well dissected land surface, if they had not been cut away by the waves. The competence of the waves for such a task of small-island destruction is proved not only by the island-tying sand reefs but even better by the strong cliffs that truncate the outer side of the near-shore islands and the main headlands. Indeed, along parts of the coast where embayments happen to be wanting, the shore cliffs are continuous for miles together in somewhat ragged pattern (Fig. 185), and the cliffs usually plunge to a moderate depth below present sea level, as is shown by soundings of ten or more fathoms close to the shore line.

It is of course possible that the southern coast, where the descent to deep water is relatively rapid, never had so many islands offshore as the northern coast, where the descent to deep water is more gradual; but it seems improbable that any process of down-faulting or down-flexing along the southern coast could have left it so free from islands as it now is. The total absence of islands there is therefore ascribed to abrasion. But in any case the abundance of little-cliffed islands off the northern coast

Fig. 185—Embayments in the cliffed coast of New South Wales, north of Sydney, HO 1861 (right); cliffed coast of New South Wales south of Sydney, HO 1861 (left).

is inconsistent with its having been reef-free while a broad continental shelf was formed there.

The contrast between the northern and southern stretches of the east coast of Australia is therefore, as above noted, impressive and illuminating. I had small opportunity of getting a good offshore view of the cliffed coast of New South Wales, but shortly after seeing the non-cliffed Queensland coast, my homeward voyage gave me a gratifying sight of the great cliffs at the northern end of South Island, New Zealand, as in Figure 186. Their contrast with the sloping coast back of the Great Barrier Reef was most convincing.

The Great Barrier Reef and the Glacial-Control Theory

Let a statement above quoted from the exposition of the Glacial-control theory concerning the Great Barrier Reef now be recalled: "There is no need of believing that the entire shelf [of the Queensland coast] . . . was formed by Pleistocene wave-benching." The reason for this statement was perhaps that to cut a shelf or rock platform across the whole width of the 50- or 70-mile lagoon would be too great a task for low-level abrasion in the Glacial epochs, to say nothing of the difficulty that the non-cliffed

FIG. 186—Cliffed mountainous coast, north end of South Island, New Zealand.

lagoon islands would have offered to the abrasion of a platform behind them. But if the large-scale charts of the lagoon are now examined in the hope of finding the line where the abrasion of a sub-lagoon platform ceased, thus leaving the preparation of the inner half of the lagoon floor to some other process, the hope will be disappointed. The lagoon depths show no significant difference on the outer and inner side of any line that can be drawn roughly parallel to the outer barrier reef. The inner area, where subsidence and deposition must have acted alone, has about the same depths and about as smooth a surface as the outer area. Hence, if so smooth a lagoon floor of so normal a depth as that of the inner area can be prepared without the aid of low-level abrasion, there seems to be little need of calling upon that process to produce a smooth rock platform beneath the smooth lagoon floor in the outer area.

Summary for the Great Barrier Reef

It is advisable to maintain a suspended judgment as to alternative explanations for scientific problems concerning which no decisive evidence is forthcoming; but it is as difficult as it is unnecessary to do so in a problem concerning which the evidence for one explanation and against its alternate is abundant and convincing. In view of the facts noted in the preceding paragraphs, I find it impossible to accept the idea that the Great Barrier Reef of Queensland has been recently built up from a continental shelf of unconsolidated sediments that was prepared, previous to reef establishment and upgrowth, under conditions such as still prevail on the coast of New South Wales. In that case the Queensland coast should resemble the New South Wales coast; but as a matter of fact the two coasts

are strikingly unlike. On the other hand, I find it difficult not to accept the alternative idea that a barrier reef has been long established off the Queensland coast and has long continued its upgrowth during the subsidence of its foundation, because the features of the coast behind the reef are essentially such as should be developed under the protection that a long-existent barrier reef would provide. But in any case, the independent development of a great barrier reef by organic processes in the warmer waters and of a great continental shelf by inorganic processes in the cooler waters of the same sea is eminently possible. Indeed, had torrid Queensland been separated by a strait from temperate New South Wales, the independent development of the organic reef off the torrid coast and of the inorganic shelf off the temperate coast might never have been doubted. Hence, in spite of the many epitaphs that have been written for Darwin's theory of subsidence and reef upgrowth in the various accounts of the Great Barrier Reef above referred to, the old theory seems still to have vitality in it. Indeed, it offers a much better explanation for this greatest reef of the world than any other theory yet invented.

Barrier Reefs of the Louisiade Archipelago

The Louisiade Archipelago, HO 2955, 2956, 2957, a more or less submerged eastward extension of New Guinea, includes several barrier reefs that merit attentive study. The few sources of information about them, apart from the excellent charts, are found in the writings of Macgillivray, naturalist on the British surveying ship *Rattlesnake* (1852, Vol. 1, pp. 188, 210, 232), on which Huxley, then a youth of 22, as assistant surgeon found extreme discomfort (1901, Vol. 1, p. 54); also in the later writings of Thomson (1889) and Maitland (1892, 1905). The chief island, Tagula, 30 miles long by 9 across, with ten summits from 1330 to 2645 feet in height and a well embayed shore line, consists, like its numerous lagoon satellites which form the so-called Calvados chain, of strongly deformed and greatly eroded schists and slates. These rocks are similar to those of the northern mountain range of New Guinea, of which they are manifestly the once continuous but now interrupted extension. As such they, like the continental rocks of New Caledonia and eastern Australia, give more satisfactory evidence of subsidence than is afforded by volcanic islands. The smaller islands of Rossel to the east and of Panniet and Misima to the northwest are of similar structure.

Tagula and Its Great Barrier Reef

Tagula and its satellites are surrounded by a wonderful barrier reef, which encloses an oval lagoon measuring 112 miles east-west by about 30 across. Around the southeastern or windward side of the oval, the reef flat is 2 miles or more in width and is interrupted by only four passes in a curved length of 110 miles. The barrier reef becomes a narrow fringe

(Fig. 187) along 6 miles of the mid-north coast of the main island, probably because of steeper submarine slopes or of island warping; yet even there the large-scale chart gives no indication of plunging shore cliffs. Hence it cannot be believed that the great Tagula lagoon occupies a former land area that was cut away by low-level abrasion. The same conclusion is reached from an examination of the many members of the Calvados chain and of the almost-atoll islets on the northwest. A few of the islets appear to be moderately cliffed, as is shown in a special article that I have published on this group (1922a); but as a rule their slopes descend gradually into the lagoon waters. In the northwestern half of the oval, the reef is broken by many passes and is peculiar in having its successive parts in the ringlike form of small almost-atolls or atolls, as in Figure 188. The great lagoon is divided by the Calvados chain into a smaller northern and a larger southern part, both of which have remarkably smooth floors, with depths usually from 25 to 35 fathoms and with maximum depths of 49 and 46 fathoms.

Tagula and the other islands of the archipelago must be regarded as unstable not only by reason of their nearness to New Guinea, a notably unstable land mass, but also by reason of the unlike behavior of the Louisiade islands among themselves, two of which bear elevated fringing reefs, as will be told in Chapter XV. One of these, Misima, is of particular interest.

From these facts it must be concluded that Tagula, standing in a region of demonstrable instability and bearing clear indications of subsidence in its own embayments yet without any sign of having been cliffed by low-level abrasion, has nevertheless had developed around it a reef-enclosed lagoon floor of large extent, of remarkable smoothness, and of a depth appropriate to its area. The depth is, indeed, but little less than that of the large, open-Pacific, almost-atoll lagoon of Truk in the western Carolines. It may well be that further study of this island will disclose additional matters of significance in its history; but as it now stands the island, its superb barrier reef, and its smooth lagoon floor are eloquent witnesses for Darwin's theory.

The little loops and rings constituting the western part of the Tagula barrier reef deserve further mention, because they seem to offer a possible explanation for the somewhat similar little atoll rings constituting the Maldive reefs west of India in the Indian Ocean. I have suggested in my special article on Tagula (1922a) that a barrier reef of normal form was once built up here; that the northwestern part of the reef was moderately uplifted after it was formed, dissected into residual masses while uplifted, submerged by subsidence after dissection, gained small reef rings around the residuals as it subsided, and now exhibits the surviving summits of the residuals as islets in the reef rings, as in Figure 188. As this explanation is based only on the facts recorded on the chart, its verification must await local study.

Rossel and Its Reef Loops

Rossel, a smaller schist island, 20 miles east-northeast of Tagula and the easternmost member of the Louisiade group, 18 by 8 miles, 2750 feet high, has a well embayed shore line. It is peculiar in that the fringing reefs,

FIG. 187—Part of Tagula Island, Louisiade Archipelago; BA 2124.

which border it on the north and south, extend to the east and west in well developed barrier-reef loops, probably by reason of differences in submarine slopes, or possibly by reason of island warping, a process that has not ordinarily been considered. Its lagoons are of normal depth although, like its neighbors, this island must be regarded as owing its reef loops to upgrowth during subsidence.

Resolution of One Great Barrier Reef into Several Smaller Ones

The strongly deformed structures and the maturely eroded surfaces of the Louisiade islands suggest, as already intimated, that the islands once, when standing higher than now, formed part of a mountain range continuous with the northern range of eastern New Guinea. It should also be

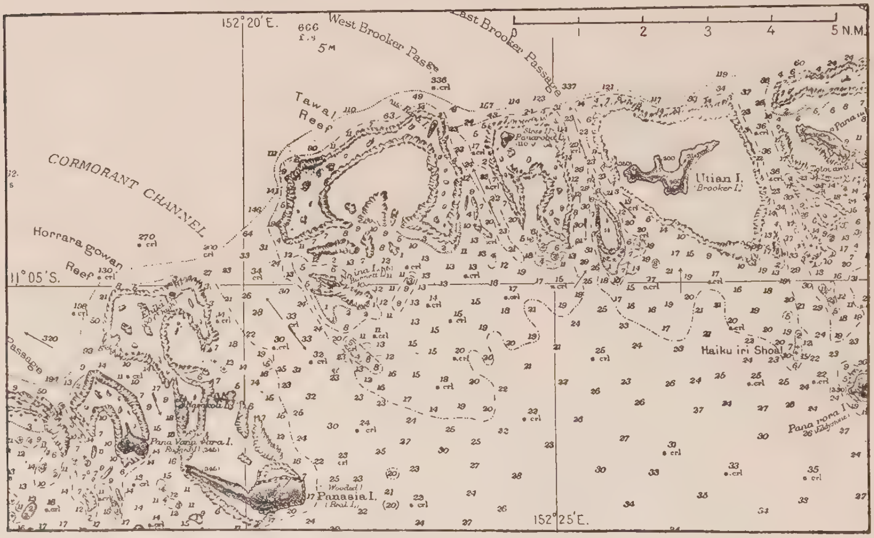


Fig. 188—Small reef circuits in the northwest part of the Tagula barrier reef; BA 1477.

inferred that the eastern end of the range lay beyond Rossel, the easternmost member of the group today. Since then the range has been subdivided or resolved into an archipelago by subsidence. A fringing reef, initiated in an early stage of the subsidence before the range had been subdivided, should have run all around its base, north, east, and south, in a continuous contour line. If such a reef had, during the later and long continued subsidence of its foundation, grown up uninterruptedly till now, the whole archipelago would be enclosed in a single barrier-reef loop of great dimensions, extending eastward from New Guinea. The fact that such a single barrier is now replaced by several individualized barriers suggests that the initial single reef was drowned by rapid subsidence—perhaps several of its successors were similarly drowned also—and that the barriers of today were initiated as fringing reefs of new generation after the resolution of the range into the present archipelago had been accomplished.

Rapid changes of level for this region are proved, as will be told in Chapter XV, by the elevated fringing reefs of Misima, not far northwest of Tagula, and by the elevated reefs on the mountain slopes of eastern New

Guinea, at a height of 2000 feet as reported by Maitland and of 3000 feet as reported by Levesey. Hence the above method of developing individualized barriers in an advanced stage of subsidence from a single fringing and barrier reef of greater size in an earlier stage—in other words, of resolving a single great barrier into several smaller ones—has the commendable quality of not involving any extraordinary assumptions for the New Guinea region. If detailed soundings are made hereabouts, it is possible that some indications of the successively drowned barriers of intermediate stages may be discovered; and it is highly probable that such soundings will discover some completely drowned islands, more or less terraced, to the east of Rossel. A memorial of one such island seems to be preserved in Pocklington atoll, 18 by 3 miles, 100 miles east of Rossel.

Continuation of Barrier Reefs in Fringing Reefs

A number of the barrier reefs described on the foregoing pages of this chapter are continued in part of their circuit as fringing reefs. Thus the barrier reef of Viti Levu, Fiji, becomes a broad fringe on the southwestern curve of the island (Fig. 142); and the barrier reef of Vanua Levu in the same group becomes a fringe around the slender northeastern point of the island, which terminates in Cape Undu (Fig. 144). Ngau, also in Fiji, has a barrier-reef loop on the west and a fringe on the east coast (Fig. 37). Similarly in the Louisiade Archipelago, the good-sized island of Tagula, around three sides of which sweeps one of the greatest barrier reefs of the coral seas, has the reef join its northern coast as a fringe for 6 miles (Fig. 187); and Rossel, a smaller member of the same group, has a barrier reef which makes loops to the east and west but fringes the island shores on the north and south. Fringing reefs thus associated with barrier reefs are supposed, as Dana emphasized, to mark exceptionally steep submarine slopes. As such they have presumably been built upward in considerable thickness during about the same measure of subsidence as that which has determined the upgrowth of the associated barrier reefs. Thus they differ from newly established fringing reefs of a second generation, which, being originated on a new shore line after a rapid subsidence, may have small thickness.

Barrier Reefs of New Guinea and Neighboring Islands

The Great Barrier Reef of Southeastern New Guinea

Eastern New Guinea is peculiar in having no reefs or only narrow fringes along its northern coast, as described in an earlier chapter, while its southern coast is fronted by a fine barrier reef, HO 2945–2949, for 380 miles eastward from the muddy delta of Fly River. The enclosed lagoon is from 5 to 20 miles wide; the coast is embayed but not cliffed. This long reef is slightly submerged (Fig. 189) in two stretches of 60 and 140

miles, where it is known as the "sunken barrier." Significantly enough, the lagoon, which elsewhere has moderate depths of 20 or 30 fathoms, there has the unusual depths of from 45 to 59 fathoms. In view of the instability of the region and of this local deepening of the lagoon, the two submerged stretches of the reef are better explained by local downwarpings of a previously formed, normal reef than by local failure of upgrowth on a stable foundation. It is indeed very possible that, in time, the now sunken barrier may be built up to sea level again.

The eastern extremity of the great island, HO 2950–2953, is divided into two points, the southern one of which, itself well embayed, is continued in two embayed islands, Sideia and Basilaki, with fringing reefs around their headlands. The great barrier reef, in part submerged, passes 20 miles to the south and then advances toward the outlying Long and Bramble Haven atolls; but there is no corresponding barrier on the north. In spite of the many signs of instability in this region and in spite of there being no signs of low-level abrasion in the way of plunging spur-end cliffs on the islands, the broad lagoon hereabouts has ordinary depths of 30 or 40 fathoms.

Barrier Reef Islands North of New Guinea

The numerous islands north of New Guinea exhibit a variety of coastal and reef features, but the reefs have not been well described. The east side of the Gazelle Peninsula, which forms the northern extension of New Britain (Neu Pommern of later German naming), has a slightly irregular shore line, HO 2970, without either cliff, reef, or bank; but around its northwestern angle a fine barrier reef follows 22 miles along the north coast and 40 along the west coast, departing 6 miles from the shore at the turn and there enclosing a lagoon up to 40 or 47 fathoms in depth. This clearly suggests a depression to the northwest, perhaps associated with an elevation to the southeast.

Regarding a reef on the island of New Hanover (Neu Hannover) the report of the German exploring vessel *Gazelle* states: "Vor einer Küste, welche die Anzeichen einer recenten Hebung an sich trägt, liegt ein Lagunenriff, dass in seinem weiteren Verlauf sich direct in das Strandriff fortsetzt. Dass dieses Riff nicht in die Kategorie derjenigen fallen kann, welche nach der Darwin'sche Hypothese durch Senkung der Küste entstanden sein sollen, liegt hier auf der Hand" (1889, p. 236). This over-easy decision is not compulsory. Whatever indications of upheaval the coast may present, a later subsidence by which the formerly greater upheaval is reduced to its present measure would produce an offshore barrier; and this much disturbed region abounds in alternating movements of that kind. As to the continuation of the barrier reef by a fringing reef, that has been shown to take place, probably by reason of differences of submarine slope, on several members of the Louisiade Archipelago, the reefs of which admirably exemplify Darwin's theory.

Farther west, Admiralty Island, BA 769, about 55 by 12 miles across and 3000 feet in height, according to the *Challenger* report consists "for the most part of undulating land . . . the coast is . . . here and there indented by deep bays. . . . Off the coast at varying distances, are a series of [discontinuous] coral reefs forming natural breakwaters" (1885, p. 699). The chart shows this barrier to be best developed off the northwest corner of the island, where it is 7 miles long and encloses a lagoon 3

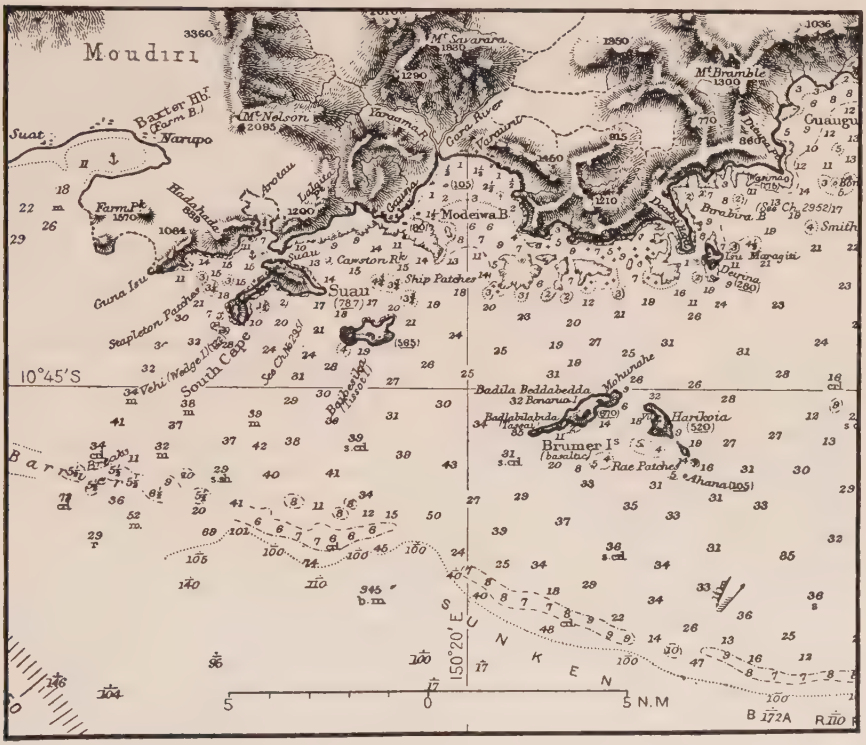


FIG. 189—Submerged barrier reef, south coast of New Guinea; HO 2950.

miles wide with the normal depths of 20 or 30 fathoms. The "deep bays" of the island suggest subsidence, although no inference to that effect is set forth in the *Challenger* text.

About 90 miles west-northwest is Hermit Almost-atoll, to be described in a later chapter; and 60 miles farther in the same direction is Ninigo Island, HO 2969, 15 by 18 miles, with non-cliffed shores, encircled by a barrier reef which encloses a lagoon up to a mile in width and with maximum depths of 52 and 55 fathoms. Here the rapidity of island subsidence would appear to have been greater than usual. Four near-by atolls will be later described, when the significance of their association with barrier-reef islands, which appear to have suffered subsidence, will be emphasized.

Barrier Reefs in the Dutch East Indies

Molengraaff's valuable account of this region (1922), already referred to in connection with the shallow and nearly reefless Sunda Sea, recognizes two stable areas, one on the northwest, including most of Borneo and the northeast sides of Java and Sumatra as well as the intervening shallow Sunda Sea, and another on the southeast, including the southwestern part of New Guinea and the northwestern part of Australia with the intervening shallow Arafura Sea; also an intermediate unstable area of many islands and deep, enclosed sea basins. The stable areas have, as already told, no elevated reefs, few barrier reefs, discontinuous fringing reefs, a small number of reef islands in the Sunda Sea north of Java and of atolls in the Arafura Sea northwest of Australia. The intermediate unstable area, here to be considered, has few well developed sea-level reefs, probably because of the rapid changes of level that have recently taken place there, as shown by numerous unconformable elevated reefs.

The Long, Imperfect Barrier Southeast of Borneo

The only important barrier reef of the unstable region rises from the eastern border of the shallow Sunda Sea floor, southeast of Borneo, and, although discontinuous and frequently failing to reach the sea surface, it may be traced by soundings for over 300 miles. Its situation suggests, to my reading, that a reef has probably been growing there since the first downwarping of a former land margin in Pliocene times, and not, as Molengraaff explains, only during and since the rise of the ocean over the muddy margin of the shallow Sunda Sea in Postglacial time. Brouwer concludes that this great reef "evidently originated from a fringing reef which in late Pleistocene time extended along the east coast of the former Sunda land, which is now partly submerged" (1923); but so late a date for its origin does not seem compulsory. Details of this region are given on Dutch charts 127, 128, which also show the Little Paternoster reefs rising in imperfect atoll form from deep water farther east. These atoll reefs are here mentioned because of the support offered by them for the view that the imperfect barrier on the margin of the Sunda Bank also grew up from a deeply depressed foundation. Thus explained, this imperfect Borneo barrier reef should be associated less with the stable area to the west than with the unstable area to the east, next to be considered.

Barrier Reefs of Celebes

The Togian Islands, described in some detail by Vuuren (1920, pp. 251–256) and shown on Dutch chart 140, stand in the northern one of the two large gulfs enclosed by the long eastern arms of Celebes. They consist of maturely eroded, stratified rocks and are half a dozen in number, from 10 to 15 miles across, with heights up to 1850 feet; their shore lines are well embayed. The islands rise from a bank or lagoon floor, from 1 to

7 miles wide and from 40 to 59 fathoms deep, along the steep margin of which a discontinuous barrier reef rises nearly or quite to the sea surface. The lagoon floor or bank extends, imperfectly margined by a reef, southeast to the mid-arm of Celebes, where depths of 49, 55, 60, 62, 63, 75, and 85 fathoms are charted. This strongly suggests the recent subsidence of a previously reef-enclosed lagoon floor but at a rate so rapid that continued reef upgrowth has been only partly successful. The same chart shows, on the southern side of the Celebes mid-arm, Tomori Bay, which appears to be a broad, drowned-valley embayment. Offshore from the bay stretches a 60-mile, discontinuous barrier reef; the enclosed lagoon has depths of 53, 54, 56, and 61 fathoms. These unusually great lagoon depths again go well with the known instability of Celebes and the imperfect upgrowth of the enclosing reef.

The Spermonde reefs, HO 3065, 3066, rise in widely discontinuous patches, frequently in part submerged, on the margin of a reef-beset bank or lagoon floor of the same name that extends with a width of from 20 to 30 miles along the southwest coast of Celebes for a distance of 140 miles. The bank is from 10 to 40 fathoms deep. The reef patches are arranged in several belts parallel to the shore, which, as Vuuren notes in his elaborate account of the coast of Celebes (1920, p. 180), seem to mark successive advances of reef growth. Instability hereabouts is indicated by the occurrence of emerged reefs inland, to be later mentioned. East of the Spermonde reefs a fairly good barrier has a length of more than 60 miles; its lagoon is 25 miles wide and 23 fathoms deep; hence a normal depth is here developed on an unstable coast.

Luang, East of Timor

Luang, the third small island east of Timor, 1 by 2 miles across, is described by Brouwer as composed of deformed and eroded strata and as rising from an oval and shallow barrier-reef lagoon, 12 by 3 miles across (1920). This observer looks favorably on the low-level abrasion of a shallow platform from which the barrier reef has grown up as the Glacial ocean rose to normal level; but he does not discuss any tests by which the actuality of such abrasion can be determined. In any case the central island, as shown in a half-tone plate in his paper, is not cliffed even where the lagoon is only a mile wide. The failure of reef protection in this region during the Glacial epochs is very improbable.

As above intimated, the rarity of barrier reefs in the Dutch East Indies must be considered in association with the many elevated fringing reefs of moderate thickness; for those reefs clearly indicate, as has been shown in an earlier chapter, that, although movements of subsidence have been frequent, they have been as a rule too rapid to be accompanied by reef upgrowth. Submerged fringing reefs are probably of as common occurrence here as emerged reefs; the sea-level fringing reefs found along the embayed shore lines of the islands are probably the product of a still-stand pause

now occurring and are therefore to be regarded as close relatives of other fringing reefs at lower or higher levels.

A Barrier Reef in the Philippine Islands

As in the unstable area of Dutch East Indies, so in the unstable Philippines fringing reefs are common, but barrier reefs are almost wanting. One of the few sea-level barriers to be seen today fronts the northwest coast of Bohol, CS 4429, next east of Cebú; the reef is discontinuously developed for a length of over 30 miles, from 5 to 7 miles offshore, with a lagoon from 20 to 25 fathoms deep from which rise many reef patches. That a barrier-reef lagoon should be of normal depth in this notably unstable archipelago, where all signs of low-level abrasion are wanting, is one of the many reasons for rejecting island stability and platform abrasion when explaining mid-Pacific atolls. Later chapters on elevated reefs and submerged reefs will show that barriers have been formerly better developed in the Philippines than they are now.

Barrier Reefs in the Indian Ocean

Mayotta and Its Barrier Reef

The Indian Ocean is peculiar in possessing only one example of a well embayed, reef-encircled island; namely, Mayotta, BA 2741, 20 by from 3 to 8 miles, 2165 feet high, one of a group of four volcanic islands between northern Madagascar and the coast of Africa. The barrier-reef flat is up to a mile in width; the enclosed lagoon is from 6 to 12 miles wide and from 15 to 28 fathoms deep. The island appears to be composed of several maturely dissected cones and has a well embayed shore line. It thus contrasts strongly with the not-far-distant island of Comoro, already described as a young and little-dissected volcanic mass with a harborless and almost reefless coast. Voeltzkow, who has given a general account of these islands (1904), does not recognize the embayments of Mayotta as indicating submergence, nor does he discuss the contrast between the massive constructional form and simple shore line of the young cone of Comoro, on which erosion has hardly begun to act, and the maturely dissected cone and well embayed shore line of Mayotta. It is not unnatural that, failing to detect these phases of erosion and subsidence in the island's history, this zoölogical observer harks back to the formerly acceptable idea that the barrier reef of Mayotta is based on the rim of a gigantic volcanic crater.

Barrier Reefs in the West Indies

The best developed barrier reefs of the West Indies are those of Cuba, HO 2145. The barrier of the north coast is wanting near the eastern end of the island and again for some 70 miles near Havana; but between these

two vacant stretches the reef is well developed and at one point stands 20 miles offshore. There the lagoon, with many reef patches, has a depth of only a few fathoms. West of Havana the reef extends for 100 miles or more to the western point of the island. The barrier of the south coast, by far the greatest in the West Indies, is well shown on HO 2613, 2614, 2615, 2616; it is discontinuously developed for a length of 150 miles; its lagoon has a maximum width of 35 miles, with depths of 10 or 12 fathoms; the reef falls off into deep water on the outer side. Whatever dissection the lagoon floor suffered by low-level erosion in the last Glacial epoch has been healed over by later deposition, for the floor is now comparatively smooth, except for the many reef patches that rise from it. Three banks, 12 by 3, 2 by 2, and 10 by 10 miles across, lie not far to the south of the barrier.

Summary

The foregoing review of barrier reefs and their encircled islands is believed to furnish substantial support for Darwin's theory. The leading process of the theory, island subsidence, was taken by Darwin to explain the facts that it was invented to explain, namely the transformation of fringing reefs into barrier and atoll reefs. But it now appears that the theory succeeds equally well in explaining also certain additional facts that it was not invented to explain; namely the preliminary establishment of fringing reefs, as told in an earlier chapter, and the embayment of reef-encircled islands together with the disposal of the great amount of detritus that such islands have lost during their dissection, as told in this chapter.

These three additional facts should be pondered over, in order to appreciate the altogether unexpected and yet wholly natural, indeed inevitable manner in which, in spite of their dissimilarity, they take their places as essential elements of Darwin's theory. While the original theory took explicit account of the transformation of fringing reefs into barriers and of barriers into atolls as a consequence of reef upgrowth during island subsidence, it gave little attention to the share that subsidence might have in providing opportunity for the initiation of fringing reefs. Yet it now appears that a vigorous fringing reef can hardly be formed around a young volcanic island until subsidence begins after the island has been more or less dissected and cliffed; also, that after a fringing reef has been once initiated, its escape from being overwhelmed and smothered by down-washed detritus as well as its gradual transformation into a barrier reef depends on the continued subsidence of its island.

Similarly, while the original theory recognized that a subsiding island should diminish in size in consequence of its subsidence and recognized also that supposedly subsided islands have shore-line embayments, it did not find any proof for diminution of size or offer any explanation of shore-line embayments. Yet it now appears that the shore-line embayments of an island give good proof that its size actually has been diminished by

subsidence; and it appears also that both diminution of size and embayment of shore line are unescapably associated with the upgrowth of a barrier reef around an island that is slowly subsiding.

Furthermore, the original theory took no account of the disappearance of a great volume of detritus from an island that becomes maturely dissected as it slowly subsides; but as soon as it is perceived that the vanished detritus must be reasonably disposed of, behold, instead of our having to complicate the old theory by introducing new conditions and processes into it as a means of disposing of the detritus, its disposal is easily and completely accounted for by a previously unnoticed consequence of the fundamental postulate of the theory in its first-announced form.

A theory that is so unexpectedly successful in meeting new requirements can hardly be wrong. Yet there are still other new requirements, quite as significant as those here brought forward, to be set forth in the following chapters, of which Darwin took no account but for which his theory provides a completely satisfactory explanation as soon as attention is consciously directed to them.

Still another matter which has been presented in this chapter deserves further emphasis. This is the occurrence of broad and smoothly aggraded lagoon floors in association with embayed and uncliffed coasts; for example, the broad lagoon floor west of Vanua Levu in Fiji. It would certainly be difficult to account for the presence of embayments and the absence of shore cliffs back of such lagoon floors unless the floors were enclosed by barrier reefs while their aggradation was in progress. The Mbengha lagoon floor and the lagoon floor back of Rambi, both in Fiji, are of significance in this connection. There is no sufficient reason for believing that these floors have been smoothed by wearing down supermarine mounts, and every reason for believing that they have been smoothed by filling up submarine hollows; and inasmuch as the near-by islands are embayed and not cliffed, no process is so available for such filling up as the aggradation of reef-enclosed lagoons over subsiding foundations.

It must not be overlooked that, although good reasons have been now given for believing that barrier reef islands have subsided during the upgrowth of their reefs, the enclosed lagoons are of ordinary depth; hence the processes of lagoon aggradation must be regarded as competent to fill up the space back of the reefs. Island stability, as postulated in the Glacial-control theory, is not a necessary condition of reef formation.

CHAPTER XIV

THE SMALL ISLANDS OF ALMOST-ATOLLS

Outline of Inquiry

The problem here entered upon has for its chief object to determine whether the islets of almost-atolls present the features deduced for small islands from the Glacial-control theory or from Darwin's theory. The inquiry is important because almost-atolls are, in their outspokenness, of much greater value as witnesses to their mode of origin than atolls are in their taciturnity; hence although almost-atolls are not nearly so numerous as atolls, the evidence they furnish is of large value. The alternative features of the two theories as explained in Chapter VI are that, under the Glacial-control theory, almost-atoll islands should have plunging cliffs on their exterior sides, while under Darwin's theory they should not be cliffed at all. In my opinion nearly all examples of almost-atolls are critically decisive in favor of Darwin's theory, as I have pointed out in a special article (1920); all the more so when the well cliffed islets that surmount certain rimless banks in the marginal belts of the Pacific are recalled.

The Mangareva or Gambier Islands

The Mangareva Islands, HO 2024 (Fig. 190), situated south of the Paumotu group of atolls near the southern margin of the Pacific coral seas, are volcanic in origin and eight in number, the largest being 4 by 2 miles across and 1300 feet high. The shores of the largest one are almost of skeleton outline, with several wide-open reëntrants separated by tapering points. All the islands rise from the lagoon of a narrow and discontinuous reef ring, measuring 12 by 15 miles across. The reef flat bears a number of sand islets in the northeastern part of its circuit but is submerged in the southwestern part to depths of from 3 to 9 fathoms; and this suggests a gentle tilting. The lagoon is generally less than 20 fathoms in depth. The area of greatest depth, 40 fathoms, is charted near the lagoon center, well within a polygon defined by the little islands and therefore inaccessible to low-level abrasion. Many photographs of the islands accompany Agassiz' detailed description (1906, pp. 62–75; Pls. 57–91); most of them, taken from near sea level, do not illustrate shore-line features clearly. Many of them, however, one of which is outlined in Figure 191, make it clear that the island slopes are maturely eroded and that their spurs decline gradually into the lagoon waters. Other plates show nearly horizontal lava beds outcropping in steep-faced benches on the eroded slopes, and thus clearly indicate that great erosion has taken place since eruptive construction ceased. A few spurs plunge

somewhat abruptly into the lagoon, as if the lava-bench cliffs, which occur elsewhere at mid-height on the slopes, happened to occur there at sea level. Abrasion has had no share in their sculpture.

Dana wrote of these islands as follows: "The very features of the coast —the deep indentations—are sufficient evidence of subsidence to one who has studied the character of Pacific islands; for these indentations corre-

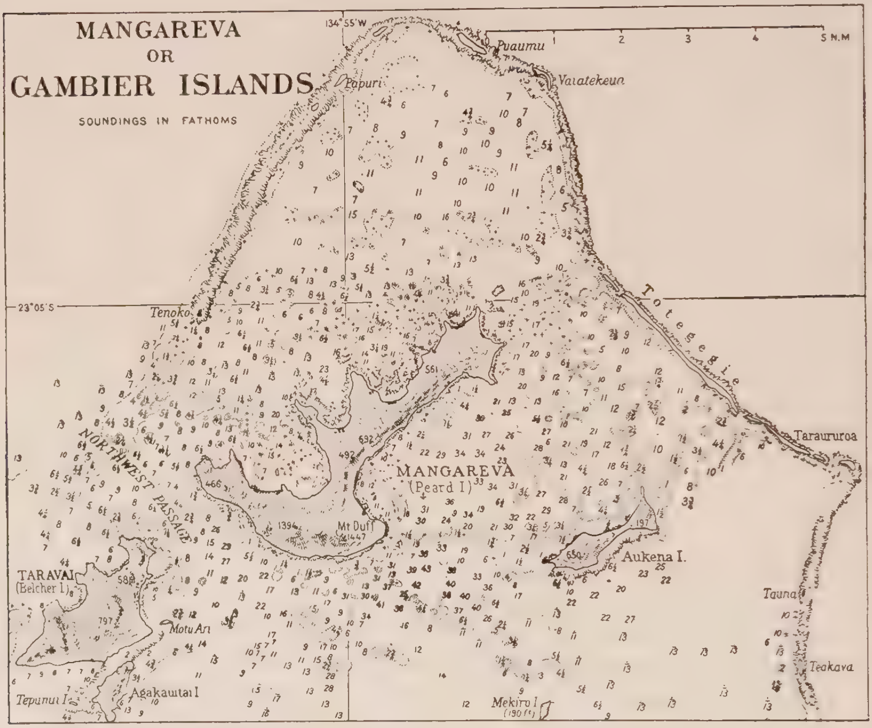


FIG. 190—Mangareva or Gambier Islands and their almost-atoll reef; HO 2024.

spond to valleys and gorges formed by denudation during a long period, while the island stood above the sea" (1853, p. 94). This rather overstates the case; for the islands are too small to show well defined valleys and too far advanced in their cycle of erosion to possess gorges. But that the reëntrants of the shore line result from the subsidence, indeed, the rather strong subsidence of islands with broadly opened valley heads is clear enough. In Agassiz' interpretation of the islands he took little account of erosion and none of subsidence; he ascribed the visible forms chiefly to eruption and regarded the open bays of the largest island as "remnants probably of small craters which flanked the large crater, of which Manga Reva [the largest island] forms the western rim"; and he took the deepest part of the lagoon, near this island, to mark the cavity of the main crater (1906, pp. 64, 65). Dana's interpretation is much to be preferred.

THE ALMOST-ATOLL OF CLIPPERTON ROCK

Clipperton Rock surmounts a small and lonely reef on the far northeastern side of the Pacific coral seas in latitude 10° N, longitude 109° W. The reef ring is about two miles in diameter, and the enclosed lagoon has well certified soundings of 55, 40, 42, 45, and 52 fathoms, which give it a depth altogether unusual for a lagoon of so small a size. The rock, which

FIG. 191—Outline of a Mangareva spur end. (From photograph by Agassiz, 1906, Pl. 71.2.)

rises directly from the reef, not from the lagoon, is hardly more than 300 or 400 feet in diameter; its height is given as 120 feet by Pease (1863) and 60 feet by Wharton (1898, including a cut from a photograph). The eccentric position of the rock in the reef is presumably the result of its unsymmetrical submarine slopes. The slopes of the rock are somewhat suggestive of cliffs; hence the evidence of this example is not decisive.

THE GREAT ALMOST-ATOLL OF TRUK

The great almost-atoll of Truk, HO 1752, in the west-central part of the Caroline group, is from 30 to 35 miles across; it is the largest reef ring in the open Pacific. The lagoon, generally with depths of from 20 to 30 fathoms, has according to German surveys two soundings of 58 fathoms in its eastern part. It contains 16 or more small, mountain-top islets, none of which, according to the photographs published by Agassiz (1903a, Pls. 191–193), have cliffed slopes. The highest one rises 1600 feet; none of them is large enough to show drowned-valley embayments. The maximum depth of the lagoon is still, in spite of some Postglacial accumulation of detritus, nearly twice as great as Daly's calculated lowering of the Glacial ocean; and this, as well as the non-cliffed slopes of the islets, excludes the action of low-level abrasion on a still-standing Preglacial structure.

In view of the great erosion by which the islets have been reduced to their present forms, and in view also of the general smoothness of the lagoon floor between them, it does not seem possible that the present configuration of the floor "is mainly due to orogenic conditions" or that

"the great depths of parts of the lagoon represent valleys formed at the time of upheaval of the original mass of Truk, the spurs separating them having been planed off to form the great platform," as Agassiz inferred (1903a, p. 358). On the contrary, all the features of the islets, lagoon, and reef are best explained by advanced erosion of a primitive island, associated with prolonged subsidence, strong reef upgrowth, and broad lagoon-floor aggradation.

The Almost-Atoll of Aitutaki

Aitutaki, the northernmost member of the Cook group, HO 2000, may be classed with almost-atolls, although its subdued volcanic island, 3 miles long and 400 feet high, stands at the northern angle of the triangular reef, which measures about 7 miles on a side. The reef flat is half a mile wide and the lagoon is only 2 or 3 fathoms deep. The reason for the eccentric position of the island, the somewhat exposed northern slope of which does not appear to be cliffed, is probably to be found in the asymmetry of the submarine slopes that descend from it. To the south, they probably lead to other volcanic knobs of similar form but of less height, now submerged.

Almost-Atolls in Fiji

Budd, Argo, and Reid Almost-Atolls

Associated with the true atolls that are found in eastern Fiji are three almost-atolls, which will be here described; others will be taken up later with the elevated, more or less dissected, and now partly submerged atolls of the same region. Budd reef (Fig. 102) in the northeastern part of the group is an instructive example. Its narrow and somewhat discontinuous reef ring measures 11 by 5 or 6 miles; the lagoon has the unusual depth of 47 fathoms; three islets, a mile or less in diameter, and 370, 480, and 280 feet in height, rise near the lagoon center; several smaller ones stand farther south; a small crescentic crater, a mile in diameter and 590 feet high, rises in the northeast turn of the reef. None of the islands appear to be cliffed.

Farther south is North Argo reef, HO 2852 (Fig. 35), measuring 5 by 10 miles across, with a lagoon 21 fathoms in depth. It contains two islets; one is of coralliferous limestone, nearly half a mile long and 80 feet high; the other is said to be a volcanic rock, 60 feet high. Not far distant is Reid reef, HO 2852 (Fig. 35), 6 by 8 miles across, with a lagoon 20 fathoms deep, from which, according to Agassiz (1899, pp. 124, 125), three limestone islets rise to heights of 60, 20, and 10 feet. The form of these islets is not well enough known to qualify them as witnesses in the present inquiry.

The Astrolabe Almost-Atolls

The most perfect almost-atoll in Fiji is the nearly circular North Astrolabe reef, B.A. 167 (Fig. 192), 3 or 4 miles in diameter, northeast of

Kandavu in the southwestern part of the group. Solo islet, a volcanic rock a few hundred feet across, bearing a lighthouse, rises only about 10 feet above sea level in the lagoon center; the lagoon is 16 fathoms deep. Next south is Great Astrolabe reef (Figs. 146 and 192), a loop-like northward extension of the Kandavu and Ono barrier reef already described. This reef is strong and continuous, with a width of half a mile on the eastern or windward side, but is narrower and discontinuous on the western or leeward side. The lagoon measures 9 by 5 miles and has a depth of 22 fathoms. It includes 9 volcanic islets; the largest is nearly a mile in diameter, and the highest rises 460 feet above the sea; the space within their polygon is about as deep and as smooth as the rest of the lagoon. One of my sailboat trips in Fiji carried me near some of these islets; like the headlands of Ono, the islets seemed to have low bluffs and narrow benches nipped in their slopes by present lagoon waves; but they do not exhibit the features expectable in the residual islets of a former large and stable island, encroached upon by normal and low-level abrasion.

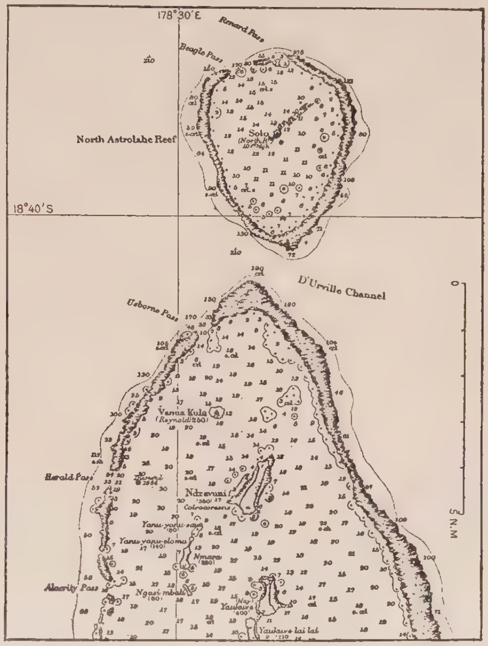


FIG. 192—North Astrolabe and Astrolabe Reefs, Fiji; BA 167.

The long and lofty island of Kandavu, bearing the young but massive volcanic cone of Mbuke Levu (Fig. 101) at its southwestern end where it is bordered by a fringing reef, has a well offset barrier south of its middle part and around its eastern end (Figs. 8, 150) and is followed to the northeast first by the smaller, sub-stellate island of Ono, then by the group of islets in the northern part of the Great Astrolabe reef, and finally by the North Astrolabe almost-atoll with little Solo rock in its center. From this it may be inferred that volcanic activity here has migrated southwestward, and that there has therefore been longer opportunity for the diminution of island size and for the resolution of single islands into several islets by subsidence in the northeastward part of the island range than in the southwestward. Moore called attention to this rather systematic northeastward decrease in island height until only Solo rock is left "in the center of a circular barrier of great symmetry" and pertinently asked: "Has not this group every appearance of a range of

mountains, the northeastern half of which is sinking beneath the ocean?" (1889, p. 204).

Barrier-Reef Loops of Vanua Levu

The two barrier reef loops, HO 2855, 2856, already described as extending southward from Vanua Levu, deserve mention again here, as they both include islets near the extremity. One loop, known as the Namena barrier, measures 4 by 12 miles; its lagoon is 20 or 22 fathoms at the deepest; its islet, Namena, is a mile long and 320 feet high, of unrecorded constitution. The other loop is 20 miles long and tapers from a width of 8 miles at its northern beginning to a slender point at its end, where it approaches the island of Makongai; the lagoon here is from 25 to 33 fathoms deep; the islet in this loop is half a mile long and 104 feet high.

The much greater barrier-reef loop, already described as extending 60 miles westward from Vanua Levu, has a width that decreases from 30 to 15 miles, and depths as far as sounded up to 46 fathoms; Round Island, less than a mile in diameter and 500 feet high, rises near the end of the loop; Sail Rock of minute diameter and 60 feet high, rises near the middle. Several other larger islands stand near the main island: one of these, Yendua, 10 miles across, 640 feet high, of remarkably stellate pattern, stands close to the southern loop arm.

The islets in these three loops of the Vanua Levu barrier are not well enough known to warrant their use as witnesses in the almost-atoll phase of the coral reef problem; but it may be noted that the Glacial-control theory would demand strong low-level abrasion for the production of the extensive rock platforms that it assumes to exist beneath the broad lagoon floors. Abrasion of such strength ought to have produced strong cliffs not only on the shores of the lagoon islets but also on those of the larger near-by islands, especially on those which are bordered only by fringing reefs or by close-set barriers, for example on the east side of Makongai; yet such cliffs are unknown. It seems, moreover, unwarranted to explain the supposed platforms beneath these large lagoon areas as having been abraded in worn-down, deeply weathered volcanic islands, because the neighboring islands are of vigorous form, and their rocks are not deeply weathered. The lagoon floors are aggraded areas.

Hermit Almost-Atoll

Hermit reef, HO 2968, 90 miles west of the Admiralty Islands north of New Guinea, is an excellent example of an almost-atoll. The reef ring measures 11 by 8 miles; the reef flat is half a mile or more in width and bears 10 small sand islets; it is interrupted by only two good passes, both of which are on the northwest or leeward side of the ring. The lagoon is generally less than 30 fathoms deep on the southeast and is there much beset with reef patches; but it is clear of patches on the northwest and there has several soundings of 46 and 47 fathoms and one of 48,

thus suggesting a recent and very gentle tilting. The enclosed volcanic islands would apparently be 10 in number, had not some of them been welded together by fringing-reef beaches so that they now number only 4. The longest of them, 3 miles over all, has two hills 700 and 800 feet high. None of them have shore cliffs. Judging by the profile views of the islands given on the chart, the rock bottom depth of the lagoon margin should be well over 100 fathoms.

Almost-Atolls in the Australasian Archipelago

North of the east end of New Guinea is Yanaba almost-atoll, HO 2942, 18 by 12 miles, with a few basaltic islets near its center; the reef is submerged to depths of from 4 to 7 fathoms in the southwest; the lagoon is about 10 fathoms deep. North of the western part of New Guinea is Aiu almost-atoll, HO 3003, 25 by 13 miles; the lagoon is from 5 to 19 fathoms deep and contains several islets, of which the largest is 2½ miles long; the highest rises 197 feet. Taka Lambaena is an imperfect almost-atoll in the Flores Sea, 16 miles southeast of Tiger atoll; it measures 18 by 2 to 6 miles, and has two lagoon islets. The small scale of the charts does not show the form of the islets in these lagoons.

The Rate of Subsidence for Almost-Atolls

An interesting corollary already hinted at in Chapter VI may be now more explicitly presented as to the rate of island subsidence in terms of the rate of island degradation. The non-cliffed islets of almost-atolls show that a volcanic island may be almost completely submerged by subsidence while it still retains a fairly vigorous relief; in other words that, although subsidence may be slower than the reduction of island height during the rapid degradation of a young island, it is apparently faster than the slow degradation that follows after the carving of a mature island. This conclusion, vague as it remains, is of value in showing the improbability of a still-stand of so long a duration that an island may be worn down to a surface of low relief and deeply weathered below its worn-down surface, as is postulated for atoll foundations in the Glacial-control theory. The conclusion is, moreover, particularly pertinent in the discussion of atoll origin, because it is not based on the behavior of large islands in a region of pronounced instability, like the Australasian archipelago where atolls are rare, but on the character of small almost-atoll islets, two groups of which, Mangareva and Truk, are in the open Pacific, where atolls chiefly occur and where the stability or instability of the atoll foundations therefore requires independent determination.

Summary for Almost-Atolls

In so far as the islets of almost-atolls are known well enough to define their form, they testify unequivocally for Darwin's theory. It is worth

noting that no coral reef theory takes particular account of almost-atoll islets in its original statement; also that Guppy's, Wharton's, and Daly's theories would demand cliffed islets, as in sector K, Figure 31, while Murray's would demand nearly flat islets, as in sector L, Figure 28; Darwin's theory alone demands non-cliffed, mountain-top islets. Thus the evidence that such islets give for the oldest of these theories and against all the others is all the more significant.

One lesson of this chapter is that the detailed form of the almost-atoll islets deserves closer attention than it has usually received from observers who have the opportunity of inspecting them. It is rarely the case that the haphazard descriptions of such islets by observers, who are unacquainted with the bearing of islet forms on the coral reef problem, are sufficiently explicit to qualify the islets as competent witnesses before the court of scientific inquiry. Yet it would be an easy matter to determine, while sailing around them, whether they have slopes that seem to slant below, or cliffs that seem to plunge under sea level.

CHAPTER XV

ELEVATED FRINGING AND BARRIER REEFS

Object of Inquiry

The chapter on atolls, which might naturally follow those on barrier reefs and almost-atolls, will be postponed, because of the little that can be learned from atoll reefs as to their origin. More profitable chapters on elevated fringing and barrier reefs and on elevated and depressed atolls will be first presented. It will thus be shown that a good number of such reefs are as communicative regarding the manner of their formation as sea-level atolls are silent. It is not, however, so much the exhibition of reef structure that uplifted reefs afford—for their structure has seldom been made out—as it is the larger relation of their limestone masses to the foundation of volcanic or other rocks which suggests inferences as to the conditions and processes of their origin. When it is discovered that the foundations possess in nearly all cases a surface of subaerial erosion, upon which the reef limestones rest unconformably, it is impossible not to conclude that the opportunity for formation of the reefs was closely associated with the submergence of the foundation by subsidence. It is therefore chiefly to the nature of the foundation surface upon which uplifted reefs rest and to the manner in which they rest upon it that attention will be here directed.

Elevated Reefs on the East African Coast

Raised reefs on the adjacent islands of Zanzibar and Pemba, near the east African coast, HO 1606, have been described by Baumann (1897, 1899) and Crossland (1902) but without recognition of their structural relations to the underlying rocks and without consideration of coastal embayments. Werth saw that the uplifted and more or less dissected reefs of those islands have been somewhat submerged, because branching bays enter their valleys (1901, pp. 134, 140). Bornhardt went farther, in recognizing that the Pemba reefs rest unconformably on their foundation and were therefore formed during the subsidence of an eroded land surface and afterwards uplifted; also that the present sea-level fringing reefs were formed during a moderate submergence which embayed the existing shore line (1900, p. 416). Ortmann (1892) described two moderately uplifted reefs near Dar es Salaam on the mainland south of Zanzibar and unwarrantably discredited their origin during subsidence because they are now elevated.

Elevated Reefs of the Red Sea

Courbon is one of the earlier writers to give an account of the elevated reefs on the coast of the Red Sea. Several essays by Klunzinger (1872;

1878, Ch. 6) include excellent description but less satisfactory explanation of a fringing reef at Kosseir on the southwest coast, lat. 26° N, HO 2813, back of which is an uplifted reef terrace. He concluded that reef formation depends on the elevation of the coast, not on its subsidence; but he took no account of the contact of the terrace limestones with their foundations, although his text indicates that it is unconformable. Baldacci described the Italian colony of Eritrea (1891) and made brief mention of elevated reefs at various altitudes up to 330 feet near Massaua and on the near-by island of Dahalak, HO 2815, but he gave no consideration to contracts. More critical records are found in Walther's careful study (1891) of the elevated reefs on the Sinai Peninsula, HO 2812. His essay is one of the earliest in which the significance of the unconformity of uplifted reef limestones on their foundation is clearly recognized. The barrenness of the desert coast must have been an aid to his observations. The highest reef, lying unconformably on a body of tilted and eroded rocks, is taken to mark the limit of the subsidence by which the peninsula had been submerged; and it is pointed out that subsidence offers better conditions for reef formation than elevation.

The most recent study of Red Sea reefs is by Crossland, who was stationed at Suakin on the southwest coast, HO 2814, as biologist to the Sudan government. A detrital plain slopes forward five or ten miles from the inland mountains of crystalline rocks to the sea; borings two miles from the shore penetrated coarse and fine detritus for over 1000 feet. The plain is interrupted by sandstone ridges which are taken to represent the little-eroded edges of displaced fault blocks, the faulting having taken place before the detrital plain was formed. Some of these ridges bear elevated reefs up to 1000 feet above sea level. Lower coastal reefs, little elevated above the shore, have been cut back by the sea while new fringing reefs have grown outward. Sea-level barrier reefs and atolls also occur. Subsidence in connection with reef growth is excluded; all the reefs are thought to have been formed in association with movements of elevation (1913, pp. 122, 131). Little attention is given by this observer to the possibly great modification of the inferred fault blocks by erosion during a higher stand of the land than now and before their partial burial by the detrital plain; it may well be that the ridges as now seen are much more the result of erosion than of faulting. In view of the proved depth of the coarse and fine detrital deposits and of the probably unconformable contact of the elevated reefs on the sandstone ridges, the exclusion of subsidence seems unwarranted.

Elevated Reefs on Islands in the Indian Ocean

The elevated reefs of Madagascar have been briefly described by Gautier (1902), Voeltzkow (1905), and Lemoine (1906), as standing at altitudes of about 300 feet along the northeast coast; they presumably have

unconformable contacts with an eroded foundation and were therefore formed in association with subsidence. As submerged reefs are reported at depths of about five fathoms off the northwest coast, where the shore is well embayed, a tilting of the northern end of the great island may be inferred; and such a tilting is all the more probable in view of the fault-like outline of the rectilinear east coast. The volcanic island of Mauritius might be included here, as it possesses some slightly elevated reefs; but it will be described in Chapter XVII because it is associated with an extensive submarine bank. The elevated atoll of Christmas Island in the eastern part of the Indian Ocean also belongs in a later chapter. Ceylon includes on its northern side a broad and low plain of coral limestone which has been described by von Richthofen (1860), who inferred that its emergence had been preceded by a subsidence of its foundation, although he did not directly mention the nature of the foundation contact. The same limestones were later described by Walther (1891), who gave more explicit statement of their unconformity with deformed and eroded foundation rocks.

Elevated Reefs in the Dutch East Indies

The greater eastern part of the remarkable Australasian archipelago appears to have been so unstable in later geological times that it has not been favorable to the development of typical barrier and atoll reefs of the open Pacific type. Where recent subsidence has taken place, it appears to have been so rapid that upgrowing barrier reefs could not keep pace with it; and hence the present shore lines bear, in spite of subsidence, only fringing reefs, thus exemplifying one of Darwin's principles as to reef origins. Certain of the islands bear several unconformable reef terraces at different altitudes, as if they had suffered intermittent uplift after rapid subsidence, or rapid uplift after intermittent subsidence, or a combination of both.

Elevated Reefs on Celebes

Wallace long ago made an excursion into the mountains of southwestern Celebes and on the way crossed an alluvial plain broken by limestone masses of mushroom shape. On the mountain flanks farther inland he found a cover of limestone resting upon basalt: such gorges, chasms, and precipices as here abound he had seen nowhere else in the archipelago. "In many places there are vertical or even overhanging precipices five or six hundred feet high," composed of "white limestone rock. Their surfaces are very irregular, broken into holes or fissures, with ledges overhanging the mouths of gloomy caverns" (1869, pp. 243, 248). The Spermonde reefs, already described, front the coast of this district. The mushroom rocks on the alluvial plain presumably owe their form to sea-water action and thus suggest a recent emergence. It is not clear whether the white limestones of the interior are of reef or lagoon origin or whether

they rest on the basalt unconformably. Nearly forty years later the Sarasin brothers visited the same part of Celebes, and their reports give many additional details. Inland from a low mangrove shore plain, rain-furrowed residuals of coralliferous limestone bear horizontal wave-cut cornices up to 100 feet above sea level. Farther on, the limestones form a continuous bench 330 feet in altitude next to the mountain base, where they rest on basalt; but it is not made clear whether the contact of the limestones with the basalt is unconformable or not. It is concluded, however, that Celebes was submerged in Eocene time, elevated in Miocene and Pliocene time, and then submerged again before its recent elevation (1901, p. 242; 1901a, p. 129): hence reef formation in association with submergence is probable.

The marked instability of Celebes is proved by several other observers. Hirschi (1913) found in east Celebes well preserved reef terraces on gabbro—and hence presumably with unconformable contacts, though it is not so stated—up to altitudes of 1650 or 1980 feet. Wanner also discovered (1910) coral limestones in eastern Celebes, lying unconformably on inclined and eroded conglomerates, up to 1320 feet above sea level; according to this observer, the formation of the limestones was thought to have accompanied an elevation of the land (1910, p. 771), although no convincing reason for this opinion is given. The same author describes the two neighboring islands of Obimajora and Halmahera, on which reef terraces were found on gabbro—and therefore probably unconformable—up to altitudes of 1040 feet. Ahlburg (1913) reports uplifted mountain blocks in Celebes bearing reef terraces, the terraces being features so familiar that the natives have a special word, *karangs*, for them; he also detected depressed blocks without reef terraces but with offshore barrier reefs. Similar diverse movements were found by Abendanon (1917, p. 560), who estimated that upheavals and depressions in Celebes since Pliocene time measure 3300 feet.

Elevated Reefs in the Moluccas

The island of Ceram, 180 by 30 or 40 miles, one of the chief members of the Moluccas, has according to Rutten (1919) hills of schist and slate in its western part, while near by is an even upland of coral limestone, 330 feet in altitude. From this we may infer that subsidence with reef formation was followed by elevation. Two stretches of the coast, 3 and 7 miles long, are of irregular pattern; and from this we may further infer that the elevation of the island was less than its preceding subsidence.

The elevated reefs of the double island of Amboyna, south of Ceram, have attracted the attention of many voyagers. The narrative of the *Challenger* records that "coral reef rock occurs raised many hundred feet above sea level, forming a steep slope . . . the rocks collected beneath the coral reef rock . . . were serpentine, granitite and altered diabase"

(1885, p. 580); but the unconformity thus indicated is not mentioned. Forbes (1885, p. 536) and Semon (1896, p. 536) give brief accounts of this reef-bearing island, but the reefs have been most clearly described in their geological relations by Verbeek (1905). One may learn from his elaborate report and the excellent maps which accompany it that the two island components, attached by a low sand isthmus, are 17 and 33 miles long and 1850 and 2890 feet high. They consist of crystalline rocks on which coral limestones alternating with gravel beds lie unconformably up to an altitude of 1770 feet. Strong changes of level in recent time are thus indicated. The possibility that some of the reefs may have been formed during the subsidence of the islands and others during their elevation—a possibility that is usually unrecognized—is here given some consideration. Although this detailed report represents a great amount of field work, its treatment of the erosion indicated by the unconformable reef contacts seems inadequate. The same observer also describes elevated reefs on many of the Moluccas up to altitudes of 1600 feet (1908) but gives little attention to the nature of the reef contacts and concludes, without full evidence, that the reefs were formed during the elevation of the islands on which they are found.

In the Timorlaut group, Yamdena, the largest island, about 100 miles long by 30 miles wide, is described by Forbes (1885, p. 333) as consisting of the cone of Laibobar, 2000? feet high, and an upland of coral limestone seldom over 100 feet in altitude; the limestones rise in precipitous shore cliffs, 60 or 80 feet high, nearly all around the island. Brouwer adds (1916, p. 39) that a body of deformed and eroded rocks underlies the limestones. It would therefore seem that when these reef limestones were at sea level they must have formed a large almost-atoll with a lofty central cone and that their formation must have been associated with subsidence.

The Lofty Reef Terraces of Timor

The activity of recent deformation in the Australasian archipelago is the subject of two papers by Molengraaff (1913, 1913a), who cites the long island of Timor in illustration of the upwarping that various other islands thereabouts have also experienced. Timor bears Pliocene or Pleistocene reef terraces, resting unconformably on greatly eroded older rocks and now standing at various heights along the north and south coasts. Some of these reefs are regarded as having been formed during a subsidence that preceded the upwarping: the highest of them along the island crest were almost-atolls, as will be told in Chapter XVI. On the other hand, Wanner (1913), while recognizing the unconformable superposition of the Timor reef terraces on their foundation, appears to have accepted without inquiry the view, which he had already expressed for Celebes, that the raised reefs were formed during the island's emergence. The same incompleteness of consideration characterizes the *Gazelle* report a quarter-century earlier (1889).

Another report by Molengraaff (1914) describes the little island of Letti, next east of Timor, as consisting of deformed and eroded rocks, on which the remnants of a dissected reef are found up to 440 feet above sea level, while a less eroded younger reef stands at 33 feet. The older reef would appear to have been formed during an earlier subsidence and the younger one during a later upheaval of the island. Brouwer (1916a) has described the small island of Moa, the second east of Timor, as having two nuclei of eroded schists, around which the remains of a higher reef are found at altitudes of from 700 to 780 feet, while a broad and well preserved younger reef terrace stands at 30 or 65 feet above sea level. The history of this island appears to have been similar to that of Letti.

Elevated Reefs on Waigeo

Wallace gave an account of Waigiou or Waigeo, a rather large island northwest of New Guinea. Its southwestern part is "almost entirely raised coral, whereas the northern part consists of hard crystalline rocks. The shores were a range of low limestone cliffs, worn out by the water, so that the upper part generally overhung. At distant intervals were little coves and openings where small streams came down from the interior." A gulf "was studded along its shores with numbers of rocky islets, mostly mushroom shaped from the water having worn away the lower part of the soluble coralline limestone." In the interior, "the country . . . was very hilly and rugged, bristling with jagged and honey-combed coralline rocks, and with curious little chasms and ravines" (1869, pp. 534, 539, 525). Subsidence would here seem to have promoted reef growth and to have been followed by a later elevation; it will be shown in Chapter XVII that the later elevation has been followed by a recent subsidence.

Elevated Reefs of Java, Sumatra, and Sumbawa

In the course of von Richthofen's travels in the Orient over half a century ago he visited Java and found on the south coast of that island an uplifted barrier reef which he regarded as having been formed during a period of subsidence; his section shows the reef resting on the worn edges of horizontal Tertiary strata, but the text does not explicitly describe the contact as unconformable. This is one of the few examples of uplifted reefs near which the present shore line is prevailingly without fringing reefs. Volz (1912, Vol. 2, pp. 225, 251, 278) has recently found raised reefs in northern Sumatra at altitudes of from 330 to 1625 feet: an unconformity between the reef limestones and their foundations may be inferred from the published sections. Extraordinary changes of level of the volcano-crowned island of Sumbawa, east of Java, have been inferred by Elbert (1912, Vol. 2, pp. 132–174) from the occurrence of reefs and benches at various altitudes above and at various depths below sea level. He concludes that, after the volcanic mountains had been deeply dissected by subaerial erosion, the island subsided in late or post-Tertiary time and

was afterwards raised by successive uplifts, so that coral-reef terraces or wave-cut benches are now seen at various levels up to nearly 4000 feet, the high reefs being a little below 2000 feet. The possibility that some of the benches and reefs were formed during pauses in the preceding subsidence is not considered. Submerged reefs around this island and its neighbors are indicated by soundings down to some 200 fathoms. It is evident that no thick reefs of a single generation, such as I believe the barrief reefs and atolls of the open Pacific to be, can be formed around or over islands so actively disturbed as Sumbawa and its neighbors.

Elevated Reefs in the Philippines

Elevated reefs abound in the Philippine Islands, but some of the earlier reports about them are discredited by later observers. Thus Semper reported (1862) a limestone mountain crest at an altitude of 3000 feet on the island of Luzon and took it to be an atoll; but its atoll-like form is now regarded as the work of erosion. Drasche found reef limestones on the same island at altitudes of 3500 and 4000 feet (1878a); but his observations have not been confirmed. An interesting account of the elevated reefs on the neighboring islands of Negros and Cebú, CS 4718, has been given by Becker; but his statements are disputed in certain respects by later observers. On Negros, 120 by from 20 to 40 miles, 7995 feet high, a series of benches on the flanks of the island were said to have excessively steep outer slopes below even crests only a few feet wide; they are composed of rough coral rock and were taken to represent a series of elevated barrier reefs (1901, p. 75). Cebú, 120 by 10 or 20 miles, 3324 feet high, is described as covered for the most part by a mantle of coral rock, 100 feet or more in thickness, reaching from the crest of the island to the shore.

Becker wrote: "The crest of the Cordillera Central in the northern part of Cebú is an even line many miles in length, which at once suggests base-levelling, but seems to be due in reality to what may be described as summit-levelling by coralline upgrowth. . . . There is one great unconformability both in Cebú and Negros. It lies between the [Miocene] lignitic series and the coral mantle" (1901, pp. 19, 69, 75). Becker concluded that "all the evidence thus far adduced, both paleontological and structural, points to a progressive uplift of the archipelago beginning in the late Miocene and still progressing" (1901, p. 79); and he was therefore inclined to accept Semper's view that the coral reefs of the two islands that he examined were formed on rising foundations. Semper's view was, however, that reefs were formed when their foundations were rising for the first time from the sea; and this is clearly negatived for these two Philippine islands by the unconformity of the reef limestones on the eroded surface of the underlying Miocene rocks. All that Becker tells of the island permits reef formation during subsidence as well as during elevation;

the only means of choice between the two possibilities lies in detailed studies of the reef structures.

Becker's view appears to be held, in essence, by Smith, who has concluded that, after sinking, Cebú "rose very slowly from the sea, so gradually that the whole island was covered with a mantle of coral limestone," much of which has been removed by erosion since emergence. "There is no apparent break in the limestone from the coral reef on the shore to the

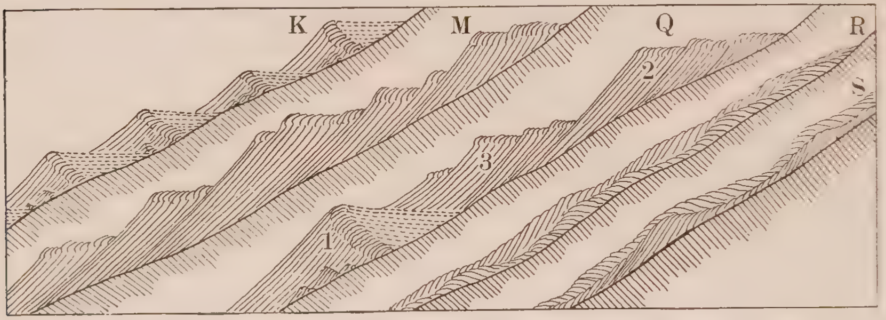


FIG. 193—Sections illustrating structure of reef terraces and veneers.

capping of the Cordillera in the center of the island at a height of 3000 ft." (1910, p. 5). This observer previously announced a different view, namely that the history of Cebú included, first, strong folding and erosion; second, subsidence and reef formation; and finally, elevation (1906, p. 1048). The level reef crest many miles in length in northern Cebú would have been, as described by Becker, an atoll when it lay at sea level; but a letter from R. E. Dickinson in Manila, dated May 18, 1923, states that the high level on Cebú has the form of a "marine plain" and bears no reef mantle where he saw it, also that it is somewhat overtopped by the hills of the island axis; hence Becker's views need revision.

Structure of Fringing-Reef Terraces

It need occasion no surprise that the detailed structure of the reef terraces on Cebú and Negros have not yet been made out in sufficient detail to determine the precise order of their formation; for a cover of forest and of jungle makes close observation of mountain sides extremely difficult on tropical islands. On the other hand, it is an easy matter to illustrate, as in Figure 193, the kind of contacts that would, if discovered, indicate the succession of reef formation clearly enough. Section *K* shows a succession of superposed reef terraces, all formed during pauses in an intermittent subsidence and then elevated without additional reef formation; an unlikely case. Section *M* shows the contrary relation of apposed reefs formed only during pauses in the elevation of their foundation. If such reefs rest conformably on a body of submarine tuffs or lavas, this re-

lation is likely enough; but if they rest unconformably on a surface of subaerial erosion, the relation is unlikely; for in that case the preliminary submergence of the foundation would have had to be too rapid for reef formation. A more probable case for unconformable reefs is shown in section *Q*, where the middle terrace is of later origin than the other two. If all three are unconformable to their foundation, then the lowest reef, 1, was probably formed first during a pause in subsidence; the highest reef, 2, probably marks the climax of the subsidence; and the middle reef, 3, marks a pause in the elevation by which all three reefs were raised above sea level. Two cases of reef veneers are shown in sections *R* and *S*. If unconformable, *S* is an altogether improbable relation; for it implies a rapid preliminary subsidence without reef formation, then an emergence and a submergence with reef veneers, and finally a rapid emergence without reef formation. Section *R* is more probable, as implying a slow subsidence and a slow emergence, both with reef veneers. No sections of elevated reefs have yet been observed in sufficient detail to be compared with ideal sections of these kinds.

Elevated Reefs on the Mariana Islands

The eleven northern volcanic members of this group have been described in an earlier section. The five southern islands, partly or wholly composed of uplifted reefs, are here introduced; the first four are shown on HO 5359. Saipan, 12 by 5 miles, 1529 feet high, is said to consist in large part of elevated reefs; its eastern side is somewhat irregular with cliffed headlands; a barrier reef lies 1 or 2 miles off the northwest shore, with a shallow lagoon and a bank extending at least 4 miles seaward from its middle in altogether unusual fashion. Tinian, 11 by 4 miles, 564 feet high, has a simple outline, generally cliffed, with a few shore reefs. According to Höfer (1912) and Seidel (1914), this island is a limestone plateau gently inclined to the west, as if it were an uptilted atoll; but the chart does not support this idea. Aguigan, 3 by 4 miles, 584 feet high, has a simple, cliffed, reefless shore. Rota, 9 by 4 miles, 1612 feet high, is a volcanic island with five terraces of coral limestone; it has narrow fringing reefs around part of its shore. Brief descriptions of it are given by Fritz (1901) and Agassiz (1903a, p. 376); but neither of these observers mentions the nature of the contact between the elevated reefs and their volcanic base. More critical studies of these islands are desirable.

Hobbs (1923a) describes this range of islands as an example of an Asiatic arc of deformation; it is adjoined by a deep trough on the east; its more eastern members from Saipan to Guam bear elevated reefs and are regarded as rising on the front of an eastward advancing anticline; while volcanic islands, more or less reef fringed, occupy a rear arc where depression with westward tilting is believed to be taking place.

Elevated Reefs of the Pelew Islands

Brief mention has already been made of the moderately elevated reefs on some of the smaller southern members of the Pelew group in the account of Semper's theory of reef origins in Chapter IV; a few details may be added here. Korror, next south of the main island of Babeltop, consists of volcanic rocks covered by reef limestones; while Peleliu, 200 or 300 feet high, at the southern end of the barrier reef which encircles the group, consists wholly of reef limestones. Unfortunately neither from Semper nor from several later writers on these islands can a satisfactory understanding of the contacts between the two kinds of rocks be gained. Sea-level fringing reefs, abundantly developed, are clearly unconformable to the volcanic rocks of the shore line. The extensive, sea-level barrier reef would seem to have grown up during a second subsidence, after the uplift of the now elevated reefs which were formed during a first subsidence.

Kubary long ago stated that some of the limestones are over 1000 feet above sea level but without giving details as to the locality or manner of occurrence; he assumed that volcanic action caused their uplift (1873). Wichman regarded the whole group as upheaved from below sea level (1875), apparently on the basis of specimens collected by Kubary. Krämer gives a good map of the group, showing the embayments of the main island and the limestone area in the south (1908), but draws no inferences from the embayments and makes no mention of limestone contacts with their basis. Friederichsen rejects Semper's theoretical views and adopts Darwin's (1901) but does not adduce either the shore-line embayments or the rock contacts in evidence of his opinion. In a thesis on these islands Wiszwianski follows Friederichsen not only in rejecting Semper's views and adopting Darwin's (1909–10) but also in giving no adequate ground for doing so. Not until Hobbs's recent visit to these islands was the unconformity of some of the elevated reefs recognized, as has been told in Chapter IV. There could hardly be better illustrations of the need of a standardized method for the examination and description of coral reefs than are furnished by the incomplete discussions in these several articles.

Elevated Reefs on New Guinea and the Islands to the North

Reference has already been made to Maitland's observations concerning the occasional occurrence of coral-limestone benches alternating with lava outcrops up to 2000 feet altitude on the mountain slopes along the northern coast of eastern New Guinea. This observer explicitly stated: "The limestones unconformably overlaid the volcanic rocks" (1892, p. 20; also 1905, p. 41); hence great and rapid changes of level are to be inferred. Observations by Levesey increase the measure of recent changes to about 3000 feet; for he stated that "on the top of a hill, judged to be over 3000

feet high . . . a large coral reef . . . stood out so clean cut, and so hard and solid, that it appeared as if it had only emerged from the sea a short time previously. Alongside the coral wall was a bank of sand containing fragments of coral and shells" (1899).

The northern coast of central New Guinea and the numerous large and small islands of the outlying archipelagoes afford many examples of sea-level reefs, mostly fringes, and of reef-terraced slopes, regarding which a number of observers have given more or less detailed accounts but too often without a due consideration of the essential factors of the coral reef problem. As far as these accounts can be interpreted, reef formation appears to have taken place as a rule during or after subsidence. Concerning the district known as Kaiser Wilhelm Land, Richarz (1910) gives a section showing steeply inclined and greatly eroded Cretaceous strata, covered with marine deposits which front on the coastal slope in terraced reefs; he infers that the reefs were made during the elevation of the eroded foundation rocks, without considering the evident possibility that they were formed during the subsidence that preceded the elevation. Brief mention of elevated reefs on this coast is made also by Finsch (1888) and Schultze (1914). Feuilletau de Bruyn records the occurrence of coralliferous limestone near the west-flowing Idenburg River in north-central New Guinea at the surprisingly great altitude of about 4500 feet (1921).

Among the islands to the north of New Guinea, Sapper has described New Ireland (Neu Mecklenburg), partly shown on HO 2970, 185 by 20 or 30 miles, 7054 feet high, as having a core of granite and andesite, the eroded surface of which indicates a period of emergence before it received an unconformable cover of marine tuffs, which prove a submergence. The tuffs are covered with terraced reefs up to 2500 or 3500 feet, thus indicating a second emergence; and, as some of the reefs are over 300 feet thick, especially along part of the island crest, this emergence is thought to have been often interrupted by submergence (1909, 1910). If it should be found that the reef limestones rest unconformably on the marine tuffs, an additional oscillation would be called for. The present shore line, as far as charted, is reefless with a rapid descent to deep water.

Dahl detected many changes of level in the small Duke of York Island (Neu Lauenburg), HO 2970, 2971, between New Ireland and New Britain (Neu Pommern), 6 by 5 miles; there are several smaller islands standing near by, and some of them look like emerged barrier reefs. Elevated reefs occur on the main island up to altitudes of 1000 feet. This observer regarded the island as having been gently tilted, because it has fringing reefs on the east and an imperfect barrier on the west; and although he makes no use of embayments or contacts he favors Darwin's theory of upgrowth during subsidence (1897, 1898, 1899). The island tilting is confirmed by von Pfeil (1899, p. 193). Much remains to be learned about the reefs of this region.

Misima and Its Elevated Reefs in the Louisiade Archipelago

Brief reference has been made above in the section on the barrier reefs of the Louisiade Archipelago to the island of Misima, HO 2955, 22 by 2 to 7 miles, 3400 feet high. It is composed of crystalline schists and bears a number of elevated reefs; its shore is somewhat embayed and has narrow and discontinuous fringing reefs; but, unlike the other members of its group, Misima has no barrier reef. Soundings of 300 or 400 fathoms are found within a distance of a mile or a little more. An unusually explicit account of the Misima reefs is given by Maitland: The "elevated reef masses, when viewed from a distance, presented the appearance of vertical walls and almost horizontal terraces, stretching often for considerable distances. The faces of these cliffs are sometimes covered with vegetation to such an extent as to present the appearance of huge walls of foliage. The reefs raised only a few feet above the sea level present along the shore white perpendicular cliffs of varying height, above which is an almost level tableland, very broken and rugged, and with a very uneven surface. Gigantic swallow holes and enormous caves have been carved out of some of the limestones. . . . The thickness of these reef masses I had no opportunity of ascertaining; it is, however, improbable from their mode of occurrence that their vertical thickness can be very great. . . . An interesting section in one of the largest caves showed the base [of an elevated reef] resting upon the upturned edges of the crystalline schists with the intervention of a small thickness of what appears to be a partially consolidated volcanic ash; in another portion of the island the base rests directly on the ancient schists" (1905, p. 37). Whether the Misima reefs were formed during the subsidence or the later elevation of the island remains to be determined; the island has clearly suffered both movements.

Panniet or Deboyne, south of Misima and northwest of Tagula, BA 1477 (Fig. 194), 4 by 3 miles, 700 feet high, appears to have shared slightly in the uplift suffered by Misima. It is said to rise from a 60-foot terrace of coral rock, which probably forms the cliffs that are charted around the northern shore; but on the south is a fine barrier-reef loop, measuring 6 by 15 miles and enclosing a smaller island; the lagoon in this loop is broadly shallow in the north and deepens gradually southward to 21 fathoms, as if it had been affected by recent tilting. Woodlark Island, southeast of New Guinea, HO 2942, 35 by 10 miles, 350 feet high, is said to be of volcanic origin and to bear coral limestones up to 150 feet above sea level; many reefs are charted in the near-by sea.

Elevated Reefs of the Solomon Islands

Reference has already been made to the elevated reefs of the Solomon Islands in Chapter IV, when Guppy's observations there were under dis-

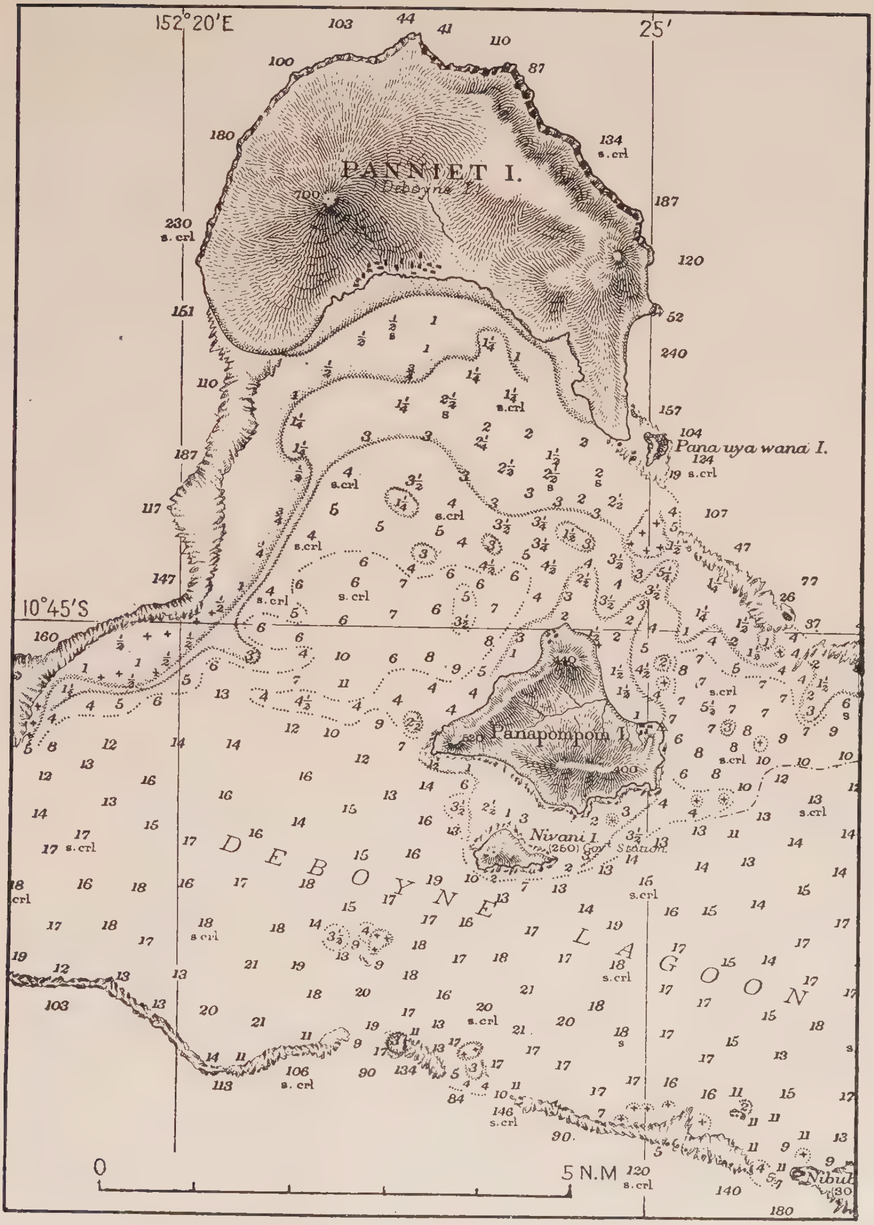


FIG. 194—Panniet, Louisiade Archipelago; BA 1477.

cussion. An account of one of the smaller islands, Fauro, and its remarkable submarine bank will be given in Chapter XVII. Fuller description may here be given of the elevated reefs, which seem to abound on some of the islands. The group as a whole, chiefly composed of volcanic rocks, is like a hollow spindle in its general pattern, trending northwest-south-

east, with a total length of 590 miles and a mid-width of 100 miles. The imperfectly enclosed interior sea measures about 250 by 45 miles. There are seven good-sized islands, of which Bougainville, the northwesternmost, HO 2896, 100 by 30 miles, bears numerous young volcanic cones, the highest rising 10,171 feet; but most of the other islands appear to have suffered much erosion and therefore to be of earlier origin. The group is peculiar in presenting examples of sea-level fringes and barriers, elevated fringes, barriers and atolls to heights of 900 feet, and submerged reefs and banks down to depths of 70 fathoms at least. The islands are therefore unquestionably unstable. Buka, northwest of Bougainville, HO 2896, 27 by 8 miles, 738 feet high, is described by Friederici and Sapper (1910) as having been tilted, because it has an elevated reef, 270 feet above sea level, on the east and a sea-level barrier reef about two miles offshore on the west. These observers also infer that a subsidence of the island had occurred before the east coast was raised; but their reasons for this inference are not clear, as they do not explicitly state that the reef rests unconformably on its foundation.

Guppy's Observations on the Reefs of the Solomon Islands

Much general information is obtainable from Guppy's work on the Solomon Islands regarding the elevated reefs they bear. He explored several of the mountainous islands and found them to be composed of ancient rocks, such as altered dolerites, highly crystalline diorites, and serpentine, flanked on the lower slopes by elevated fringing reefs up to heights of from 500 to 900 feet. Among many such reefs examined by this painstaking observer, he "never found one that exhibited a greater thickness of coral limestone than 150 feet, or at the very outside, 200 feet" (1887, pp. 70, 71); and from this he inferred not only that the reefs of the group were formed in association with its emergence but also that the small thickness of the reefs argued against the great thickness that Darwin's theory of reef upgrowth on subsiding foundations implied for mid-Pacific atolls. Gardiner appears to have shared the latter opinion, when he wrote: "Elevated reefs, which have been proved to be extremely numerous in coral reef regions, give no evidence of the very considerable thickness" which Darwin's theory demands (1903, p. 204). But instead of testifying only to an upheaval, with reef formation during still-stand pauses, the elevated reefs of the Solomons testify also to a preceding subsidence, for the reefs evidently rest on an eroded surface of volcanic rocks. Furthermore, inasmuch as the present shore line below the elevated reefs is embayed by the entrance of the sea into valleys that were apparently eroded in the mountain flanks before the reefs were formed, the preceding subsidence must have been of greater measure than the following elevation. The small thickness of the elevated reefs, instead of testifying to the probably small thickness of barrier and atoll reefs in the open Pacific, testifies rather to the rapidity of the subsidence by which the islands in

FIG. 195—The elevated barrier reef of New Georgia, Solomon Islands; HO 2907.

the unstable region of the Solomon group were lowered to the reef-forming levels, as has been pointed out in an earlier chapter and illustrated in Figure 19.

The Elevated Barrier Reef of New Georgia

None of the elevated reefs of the Solomon Islands is more remarkable than the emerged barrier reef which skirts the northeastern side of the

long island of New Georgia, HO 2906, 2907, and the northern side of the smaller island of Vangunu, next east. The reef forms a narrow ridge or wall 50 miles or more in length with a height of from 140 to 180 feet, as in Figure 195; and if a farther series of narrow islands represents the discontinuous eastern extension of the reef, it there reaches heights of 198, 226, and 257 feet. The reef is peculiar in being sometimes developed in two parallel lines, not far apart, thus resembling the double barrier reef (Fig. 7) which fronts part of the north coast of Vanua Levu, Fiji. Chart 2907 contains the legend: "Both the inner and outer barrier islands present an even-topped appearance and are about 180 feet in height; those raised [reef patches] within the lagoon are about 90 feet high. Where cliffs occur they are perpendicular and are about 140 feet high." The continuation of this raised barrier along the western part of the northern coast of New Georgia is not clearly shown on Chart 2906, probably because the lagoon floor is there laid bare, thus attaching the reef wall to the main island; but several notes on the chart indicate the occurrence of the reef for many miles.

If we now return to the southeastern end of New Georgia the barrier reef seems to be buried along the eastern side of Vangunu under a younger cone, Gatukai, 5 miles in diameter and 2912 feet high. To the south of Gatukai the reef is submerged instead of elevated; it is there charted as lying under about 5 fathoms of water at a distance of from 3 to 7 miles from the shore. Then emerging, it follows the southwestern side of New Georgia for 30 miles as a wall, 130 feet high for the first half of that distance where it encloses a flat lowland and 200 feet high for the second half where it encloses a shallow lagoon. Farther west, beyond the great cone of Kulambangra, the reef continues either at sea level or a little above for 25 miles to the northwest end of a long loop that is directed toward the outlying island of Gizo, 2 miles beyond. That island, HO 2902, seems to show tilting, as it has a close-set barrier reef on the northeast and a nearly rimless bank slanting down to depths of 50 fathoms on the southwest.

If a return is now made for the second time to the southeastern end of New Georgia and if we then continue seaward, the skeleton-like Pavuvu or Russell Island, HO 2908, is found, apparently representing a dissected and well submerged cone, for it is now resolved into a group of small reefless islands. The absence of reefs here suggests that the submergence of the dissected cone was rapid: no soundings are charted near by.

In review it may be said that the instability of New Georgia is clearly shown by the varying heights and depths of its former sea-level barrier reef; and the association of subsidence with the formation of the barrier is equally well shown, near the southeastern end of the island at least. There Vangunu Island, although it must have been raised on its northern side when the barrier reef was raised, still has a well embayed shore line; thus indicating that the recent upheaval was not so great as the previous depression. It might be added that the coral seas afford no finer exempli-

fication of Darwin's theory of barrier-reef formation than is here shown, were it not that the elevated barrier of Mangaia in the Cook group is a finer example still, partly in being of more concise dimensions and of simpler displacement and therefore more easily apprehended, and still more in having been recently studied by a trained geologist, as will be told below.

Elevated Reefs in the New Hebrides

The islands of the New Hebrides group, HO 2027, including a dozen of good size and a score of smaller ones, are arranged in the form of a slender Y, nearly 400 miles in length, north and south, over all. The long stem, trending somewhat to the southeast, includes four wide-spaced islands; the two V-like arms include the other eight of the larger members, those in the western arm being of larger size than those in the eastern. The slender eastern arm is prolonged northward by the small Banks and Torres groups, HO 2877, 2878, and farther on by the Santa Cruz group, HO 1985, already briefly described. All the members of the New Hebrides group are of volcanic origin, and several of the volcanoes are still active. The volcanic rocks include heavy beds of foraminiferous tuffs of submarine deposition. Many of the islands bear raised coral limestones. Sea-level fringing reefs are of frequent occurrence.

Many voyagers have reported briefly on the geological features of this group. Goodenough states that "five distinct and wide terraces [presumably raised reefs] are seen all along the south coast" of Erromango, in the middle of the Y stem; that the back slope of Havannah harbor on the west coast of Efate, next north of Erromango, shows "successive terraces of coral with wide levels"; and that "St. Bartholomew island . . . together with all the southern land of Espiritu Santo [the largest and northwesternmost island] is in five terraces" (1876, pp. 282, 285, 331). Similar statements are made by the *Challenger* Narrative (1885), Frederick (1893), and others. A much fuller geological description of these islands, with a bibliography appended, has been prepared by Mawson (1905), whose critical studies are of much value. My voyage of 1914 gave me general views of several of the islands and a closer view of some elevated reefs on Efate.

Tanna, in the southern part of the group, HO 2027, 19 by 10 miles, 3200 feet high, includes the active volcano, Yasua, "a conspicuous object by night." The instability of this island is well shown in an account by Lawrie of the effects of an earthquake in 1878; it "caused a surge of the water at Port Resolution to rise forty feet, and to sweep everything before it, destroying all the canoes of the natives. Two minutes after the earthquake a rise of the land took place on the whole west side of the harbor, to the extent of about twenty feet. This narrowed considerably the effective anchorage of the harbor, and a lost anchor came into view where a ship had ridden safely some years previously. About a month after-

wards another earthquake caused a further elevation, so that rocks which were formerly covered with seven or eight fathoms of water are now above high-water mark" (1898, p. 322).

In a group like the New Hebrides, where movements of elevation are repeatedly indicated by elevated coral reefs, usually of the fringing class, it is natural to associate the formation of the upraised reefs with pauses in the elevatory movements of the islands by which the reefs gained their actual altitudes. Such was Mawson's conclusion; he announced that, on Efate, the "newer raised reefs occur at intervals in terrace formation down to the beach, evidently marking a succession of sea-levels resulting from sudden uplifts of the land" (1905, p. 438); and he supports this opinion by reference to the sudden uplifts of Tanna, above noted. It was therefore with special interest that, in company with E. C. Andrews of Sydney, I visited Havannah harbor on the west side of Efate during my voyage of 1914 and ascended a ravine known as Steep Gulley, which Mawson had mentioned as exposing an instructive section of reef limestones on volcanic tuff.

On making the ascent of this ravine, it became clear that the tuff beds, which lie about horizontal, are cut off in slanting steps by the benched slope of the land and that the limestones of successive fringing reefs rest against the benched edges of the tuff beds up to altitudes of 500 feet or more in what seemed to be an unconformable relation. I was inclined to regard the sub-limestone slope as essentially the work of subaerial degradation, subordinately modified by wave action at the time of reef formation. In view of these structural relations, it must be inferred that the island, after having stood for a time at least as high as now and perhaps higher, subsided and rose again; and, if so, some of the reefs may have been formed during pauses in subsidence, others during pauses in elevation. The possibility remains, however, that the island slopes are in large part landslide scarps, formed when the marine tuffs were in process of elevation above sea level, and more or less modified by weather and waves and benched with fringing reefs during pauses in the further elevation; but the benched slope of the tuffs back of the reefs does not seem to be so well explained in this way as by erosion.

The southern part of Espiritu Santo, the northwestern member of the group, HO 2883, 62 by 31 miles, 5520 feet high, seems to afford less equivocal evidence of changes of level. According to Mawson (1905, p. 477) the older rocks of that island, which have been tilted and much eroded along the western coast, are revealed also in a valley that is cut through the recent and nearly horizontal coral limestones of the "immense elevated tableland" which stands at an elevation of about 1000 feet in the southern part of the island. Such a relation demands tilting, upheaval, erosion, and subsidence before the coral limestones were formed, and elevation afterward. But repeated movements of these kinds are normal enough in this much disturbed region.

Elevated Fringing Reefs in Fiji

The Small Reef of Walu Bay

A small outcrop or patch of coralliferous limestone on the slope leading down to a little cove, known as Walu Bay, in the reef-enclosed lagoon harbor of Suva, the capital of Fiji, on the southern coast of its largest island, Viti Levu, has attracted the attention of Gardiner (1898, p. 453), Agassiz (1899, p. 116), Andrews (1900, p. 37), and Foye (1918, p. 24). At the time of my visit to Fiji in 1914, this reef patch was fairly well exposed in a quarry. Although somewhat dislocated by small faults, the reef is easily seen to lie conformably within a series of south-slanting beds of the "soapstone" or volcanic muds, already described in the account of the Viti Levu barrier reef. The opportunity for local coral growth here seems to have been provided by a thin bed of cobbles and pebbles, which probably mark the temporary mouth of an active river on its delta. After a fringing reef patch of small thickness had been formed its further growth was stopped by a cover of delta muds.

Gardiner has described several other small reef patches in the Suva district, similar in their geological situation to the little Walu Bay reef. Because of their alternation with soapstone beds he rejects Brady's conclusion that the depth of soapstone deposition is 150 or 200 fathoms,as noted in the account of Viti Levu in Chapter XIII, and regards them as shallow-water deposits (1898, pp. 453–456), a conclusion in which I fully concur. Woolnough believes that the fossils he found in the Walu Bay reef give it a date not later than Pliocene (1903, p. 464).

The conditions affecting the origin of this little reef therefore have no close bearing on the origin of coral reefs in general, except in so far as they show that something less liable to movement by wave or current action than delta muds is needed as a basis for coral growth. In this respect, however, the reef is of significant value; it suggests that when a young, cliffed and beach-rimmed volcanic island subsides rapidly enough to drown its beaches, reef-building corals may begin their growth on the cobbles and pebbles that lie in the offshore extension of the beach deposits at such a depth that they are no longer, after the subsidence, agitated by waves. The barrier reef of Tahiti has already been instanced as having probably begun its upgrowth under such conditions.

An elevated reef is described by Foye (1918, pp. 35, 37) on the south coast of Vanua Levu, with inferences as to changes of level. A few other elevated fringing or barrier reefs in Fiji will be described in the next chapter with the elevated atolls which abound in the eastern part of the group.

Elevated Reefs in the Austral Group

Rurutu, HO 2228, 6 by 3 miles, 1300 feet high, is a volcanic island bearing an elevated reef, recognized as such nearly a century ago by Tyerman

and Bennet (1832). According to a recently published account of this island by L. J. Chubb (1927), it rises to a central plateau-like ridge of moderate relief and deeply weathered soils—apparently representing a peneplain or an abraded platform of early date—on the lateral slopes of which a much eroded sheathing of limestone is supposed to be the remains of an early formed reef. It is not known whether the limestone remnants rest unconformably on the underlying slope. A much better-preserved reef forms a cliffed bench about 200 feet high on the western and 300 on the eastern side of the island, thus suggesting that a slight tilting accompanied its elevation. The limestones of this lower reef are seen to rest unconformably on the underlying lavas; and from this it may be inferred that, after a time of erosion at some such altitude as the island now possesses, it subsided a few hundred feet while gaining the reef bench and was then raised by about the same amount; but Chubb explains the reef as an outgrowth during a pause without subsidence. This is unacceptable, because he elsewhere states that "owing to the action of subaerial agents, the original form of the volcano is lost" and that the reef "rests with a marked unconformity on a sloping surface of volcanic rocks;" also that "at the base of the reef limestone is a conglomerate . . . consisting of pebbles of volcanic rock and coral fragments" (pp. 310, 309). These structural items, taken with the 200-foot thickness of the reef, clearly indicate a subsidence of that amount after a previous elevation. Basaltic lapilli occur on the bench, indicating a brief eruption after the reef was formed. A coastal plain of variable width, raised 6 feet above sea level and composed of coral débris and sand, advances to a simple shore line, around which is a fringing reef up to 1000 or 1200 feet in width. Offshore soundings are lacking.

Rimatara, 77 miles west-southwest of Rurutu, HO 824a, 2 by 3 miles across, 315 feet high, is described by Chubb, according to information received at Rurutu, as bearing an elevated reef several hundred yards wide and 20 or 30 feet above sea level around its central hills; thus its history presumably resembles the later history of Rurutu in quality but with quantitative differences; but it differs from Rurutu in being surrounded by a barrier reef about six miles in diameter.

Chubb's account of these islands closes with the interesting suggestion that they and their neighbors lie on the northwestern part of a low and unsymmetrical anticline, advancing from southwest to northeast. Rurutu, with an elevated reef and a sea-level fringe, is regarded as standing on the crest of the anticline; Rimitara, with a well-offset barrier reef, and some other islands imperfectly known are thought to be on the subsiding rear slope of the anticline, near its crest; the raised reef of Rimitara is taken to show that the island was elevated as the anticlinal crest approached it, while its barrier reef gives evidence of subsidence since the crest passed by. Rapa and Marotiri, standing farther southeast but in such a position as to suggest that they are now farther from the

anticlinal crest than Rimitara, have appropriately suffered a greater subsidence; their lack of barrier reefs is because they stand in the southern marginal belt of the Pacific coral seas. A somewhat similar case of a migrating anticline in eastern Fiji, where a much larger number of islands and reefs are involved, will be described in Chapter XVI.

Elevated Reefs in the Cook Group

Mangaia and Its Raised Barrier Reef

Mangaia, the southernmost member of the Cook group, has recently been visited by Marshall, a geologist of New Zealand, who as holder of a fellowship of the Bishop Museum of Honolulu and of Yale University has made a most illuminating report upon it. His results, communicated to me by letter in advance of publication, are in essence as follows: The island measures about 6½ by 4½ miles and consists of a central volcanic upland 550 feet in height, surrounded by an elevated barrier reef about 200 feet in height; the raised reef flat of this barrier, known to the natives as Makatea, is from half a mile to a mile wide and has a gentle outward inclination. The volcanic upland presents an even surface to which the original volcanic cone appears to have been reduced by abrasion when it stood lower than now in its undefended youth; but, after that period of complete abrasion, the truncated surface was raised to an altitude of nearly 700 feet and so greatly consumed by the retrogressive erosion of many consequent valleys that it survived only in flat and narrow crests radiating irregularly from the island center.

This erosion was followed by subsidence, in consequence of which a reef, presumably beginning as a fringe, grew up as a barrier and enclosed a lagoon. The subsidence ceased when the barrier had risen about 300 feet and the embayed ridges and crests of the dissected volcanic upland had an altitude of only about 350 feet above the sea. The reef flat probably gained its considerable breadth during a still-stand pause that marked the close of the subsidence. Then elevation again took place, raising the compound mass until the reef flat gained its present altitude of about 200 feet and giving the even crests of the central upland their present altitude of 550 feet. This elevation does not seem, however, to have been sufficient to lay bare the lagoon bottom, for the moat between the outsloping spurs of the central upland and the infacing wall of the reef is not occupied by a limestone plain but by flats which lie only a few feet above sea level and which enter between the sloping spurs in triangular swamps of much smaller size than the water embayments of the island must have been before its recent elevation. A model shows that three of the volcanic spurs reach and apparently pass under the reef wall, the limestones of which therefore must rest unconformably upon the eroded volcanic rock, thus proving that the dissection of the truncated and uplifted island took place before it subsided and became reef-encircled.

If further confirmation of this conclusion is desired, let it be noted that the little swampy flats at the bottom of the moat are entirely too small to contain the large volume of detritus that must have been removed during the erosion of the valleys above them; hence the vanished detritus must have been disposed of before subsidence and reef growth began. Indeed, in view of what has been told of young volcanic islands in an earlier chapter, the detritus was probably disposed of even before the basal fringing reef of the present barrier was established. If so, the island must have been then, as well as during its previous lower stand of complete truncation, exposed to wave attack and cut back in cliffs. Yet no spur-end cliffs are now to be seen: the spurs descend gradually and disappear under the swampy belt or under the reef limestones. Hence if any cliffs were cut around the island during its higher, pre-barrier-reef stand, they must now be buried under the reef or completely submerged; and in this case the elevation of the island and the following subsidence should be allowed greater values than are given for them above.

The outer slope of the raised reef is steep at first, then gentler to the shore, which is bordered by a new fringing reef from 300 to 900 feet wide. The drainage of the upland valleys is accomplished through underground passages in the raised reef, from which the streams emerge near the present shore line. The sides of the elevated reef are so steep and its upper surface is so rough that it can be crossed only at a few places where the natives have constructed stairways and paths.

Mangaia and Darwin's Theory

It would be difficult to imagine a clearer example of a barrier reef constructed according to the specifications of Darwin's theory than the one found on Mangaia. The only elements in which this central island differs significantly from many others are, first, the complete truncation of the island cone when it was young, low-standing, and undefended; second, the upheaval of the truncated cone before a later subsidence accompanied by reef growth began. But the introduction of these two unessential elements in no wise impugns the success of the island in exemplifying, by the occurrence of subsidence between its two upheavals, the Darwinian transformation of an upgrowing fringing reef into a full-fledged barrier reef.

Darwin's comment on the island is illuminating. From the brief account of it by certain missionaries he believed it to bear an elevated reef with a level surface about 300 feet high; he therefore concluded: "There can be scarcely any doubt that . . . Mangaia . . . and several islands in the Friendly [Tonga] group existed originally as atolls, and these have undoubtedly since been upraised to some height above the level of the sea; so that by our theory, there has here . . . been an oscillation of level—elevation having succeeded subsidence, instead of, as in the middle part of the Red Sea and at the Harvey Islands, subsidence having probably succeeded recent elevation" (1842, pp. 132, 139, 140).

It does not seem too much to say that if any conservative students of coral reefs should still question the production of barrier reefs by the upgrowth of fringing reefs, a visit to Mangaia—or in lack of that, a consideration of Marshall's report on that island—ought to remove their doubts. Indeed, the attitude of a conservative student toward coral reefs ought to be the same as that of a state inspector toward some manufactured product whose composition he desires to learn. He buys a sample unit of it in the open market and gives the sample to his chemist for analysis, feeling confident that a unit so impartially selected will fairly represent all other units of the same brand. Similarly, when the deep-seated, sub-crustal forces of upheaval raised Mangaia—this upheaval corresponding to the inspector's purchase of a sample unit in the open market—those forces cannot be supposed to have been at all influenced in locating their effort beneath a certain part of the sea floor because of the presence there of an island bearing a barrier reef at the sea surface, still less by the presence of a surface barrier reef formed in a special manner, as if in exemplification of a particular theory of barrier-reef origin. On the contrary, the forces of upheaval were entirely ignorant of and indifferent to the occurrence of a reef-encircled island over the suboceanic area of their application.

Furthermore, Marshall's analysis of the Mangaia reef is as impartial as a state chemist's analysis of a unit sample of some manufactured product submitted to him by the state inspector. The uplifted Mangaia barrier should therefore be regarded as a fair sample of practically all the sea-level barrier reefs of the coral seas, and the theory that will satisfactorily account for it deserves acceptance for all other barrier reefs also; and indeed, for most atolls as well, because the gradation of barrier reefs through almost-atolls into atolls shows that these several types of reefs must exhibit only the earlier and later stages of one evolutionary process. Hence the revelation of reef origins that Marshall's analytical investigation of Mangaia has afforded possesses an ocean-wide and not merely a local value. True, as above noted, the history of Mangaia differs from that of many other islands now encircled by sea-level fringing reefs in certain respects; but these differences are antecedent and irrelevant to the formation of the barrier reef. They have nothing to do with the reef formation.

On the other hand, in features essential to reef formation Mangaia appears to represent all other barrier reef islands. It suffered much valley erosion before the upgrowth of its barrier reef was begun, and in its then undefended state it presumably suffered also a significant amount of shore-cliff abrasion; for the generality of the early association of erosion and abrasion during the discharge of great volumes of eroded detritus is testified to directly by Réunion, Tutuila, Tahiti, and northeast New Caledonia and indirectly by many other islands. The subsidence of Mangaia which eventually resulted in giving opportunity for barrier-reef upgrowth may very well have been already in slow progress during the pre-

liminary phases of valley erosion and cliff abrasion. But not until the island was well advanced toward its present stage of sculpture can subsidence, perhaps then proceeding at a somewhat accelerated rate, have succeeded in preventing the outwash of detritus from smothering the near-shore reefs and have thus secured for them the opportunity for unin-

FIG. 196—North coast of

terrupted upgrowth. In all these respects Mangaia is the very type of a barrier-reef island. It must be, of course, still conceivable to an indoor metaphysician of the absolutist school that the structure and hence the origin of the Mangaia barrier, which when at sea level encircled a well dissected volcanic island with an embayed shore line, may differ in some significant manner from the structure and origin of other barriers similarly situated; just as it may also be conceivable to him that a tin of baking powder of a certain brand, bought in the open market, may differ in composition from the powder in all the other tins of the same brand; but the state inspector and the outdoor pragmatic geologist will regard the possibility of such differences as vanishingly small.

Geological Age of the Mangaia Barrier Reef

In one respect Marshall's results are perplexing. He reports the occurrence of the foraminifer Lepidocyclina as a fossil in the reef limestones and therefore dates the limestones as Miocene. If that date be accepted, we should be required, in view of the little dissection the reef has suffered since its elevation, to believe that after gaining its full size it had remained at sea level through most of Pleiocene and later time and had been elevated only long enough ago for the roughening of its surface. But had it remained so long at sea level, the enclosed lagoon ought to have been well filled with outwashed detritus from the central uplands and with inwashed detritus from the reef; yet it does not appear to have been thus filled. On the other hand, if the reef had been uplifted shortly after its upbuilding was completed, thus coming to be exposed to erosion during Pliocene and post-Pliocene time, it ought now to be greatly dissected; and it is not.

Thus a contradiction arises between the paleontological and the physiographic evidence as to the history of the reef; and this contradiction recalls a similar one concerning certain basin deposits in the western United States, known as the Equus beds, which Gilbert pointed out years ago, and regarding which he thought the physiographic evidence was more trustworthy than the paleontological. I am much inclined to follow his

Rarotonga, Cook Islands.

example and to accept the physiographic evidence as giving a relatively recent date for the making as well as for the emergence of the Mangaia reef and conversely to mistrust the paleontological evidence which makes the reef of Miocene date. This of course involves the assumption that Lepidocyclina has survived in this part of the Pacific longer than it has elsewhere, and paleontologists doubt such a survival. Yet, until the foraminiferal deposits of the mid-Pacific have been more closely and extensively studied than they have yet been, I am disposed to regard the above suggestion as not altogether unreasonable.

Other Elevated Reefs in the Cook Group

Marshall has briefly described three other raised-reef islands in the Cook group, all on HO chart 2000. Atiu, 2½ by 3½ miles, 394 feet high, has a raised barrier reef about 30 feet above sea level and a narrow sea-level fringing reef; the character of the island itself is not specified. Mauke, 2 by 3½ miles, has similar features, though they are less distinct. Rarotonga (Fig. 196), 6 by 4 miles, 2100 feet high, has a close-set and little-eroded barrier reef, from a quarter to a half mile wide, now about 15 feet above sea level, enclosing a narrow lagoon flat or swamp and fronting on a narrow sea-level fringe. This island is a superbly dissected volcanic mountain, rivaling Moorea in picturesqueness as well as in its demands for some reasonable way for disposing of the vast volume of detritus that has been eroded from its deep-cut and well opened valleys. I made a two-hour stop there on the return voyage of 1914, when a walk inland led me up a fairly broad alluvial flat that had been formed, apparently during the upgrowth of the now elevated barrier reef, in a wide but rather steep-sided valley in the right half of the above figure.

Here, as well as in Mangaia and various other islands already described, the amount of dissection that the embayed island has suffered below the raised reef level, in continuation with that above the reef level, appears to have been much greater than could have been accomplished by low-level erosion during the Glacial epochs; and the depth of the buried valley that I entered seemed to have been greater than the measure of Postglacial ocean rise. Moreover, the first emergence of Mangaia and the later emergence of both Mangaia and Rarotonga are clearly independent of Glacial changes of ocean level and are presumably due to movements of elevation at times that were not particularly related to the subdivisions of the Glacial period. As these movements of elevation have taken place, and as a considerable movement of subsidence is clearly proved for Mangaia during the upgrowth of its barrier reef, a smaller movement of subsidence for Rarotonga is probable in association with the upgrowth of its barrier reef. Glacial changes of ocean level and temperature undoubtedly took place in the coral seas, but the effects that they produced have not yet been identified in these islands.

Elevated Reefs in the West Indies

Crosby has described several limestone benches on the northern coast of Cuba as elevated reefs. There appears to be no question that the lowest of the benches is of such origin; concerning it he states: "The first terrace, which, for hundreds of miles, has a sensibly uniform altitude of about thirty feet, . . . is unbroken, save where rivers have cut through it. . . . The most casual observation shows that the indescribably jagged and ragged rock is a limestone [locally known as *soboruco*], and largely made up of several kinds of modern-looking corals. In other words, the terrace is a fringing coral-reef that has been lifted above the level of the sea; and looking from the perpendicular front of this ancient reef we can see distinctly that the adjacent sea bottom is paved with growing hemispheres of Astrea and Meandrina—the summit of a new reef." The reef terrace "varies in width from a few rods to a mile or more. Sometimes the ground descends away from the shore, indicating that the reef, during its formation, was a barrier reef at these points" (1884, pp. 124, 125). Then follows a passage that has been quoted in Chapter III, concerning the unconformable contacts of reefs with their foundations. The second terrace is from 200 to 250 feet in height and is more dissected; its limestones appear to be older and more altered, and their corals are less distinct. The third, at a height of 500 feet, shows signs of still greater age.

A later study of the same coast by Hill excludes all but the lowest bench from the class of elevated reefs. He writes: "The elevated benches and terraces which border the [north] coast of Cuba, with the single exception of the soboruco or modern [elevated] coast reef, are not ancient

coral reefs either topographically or lithologically, as has been asserted, but, on the other hand, are beach and erosion plains, produced by rapid elevation of the island in Post-Tertiary time, and carved from various formations, principally the older limestones, regardless of structural arrangement and composition" (1895, p. 277). This experienced observer expresses doubt as to the occurrence of subsidence in association with the formation of the soboruco reef.

Elevated reef limestones are known also on Haiti and Porto Rico; those of the latter island have been described by Berkey as lying unconformably on older formations (1915, pp. 12, 15). Those on the eastern part of Haiti, in the Dominican Republic, have been described by Vaughan and others (1921); the highest reach altitudes of 260 feet; in one locality it is noted that "to the traveller passing over this forest of corals, some still bearing their original colors, its resemblance to a modern coral reef as seen at low tide is very striking" (1921, p. 77). The elevated reefs of western Haiti, in the republic of that name, have been found by Woodring, Brown, and Burbank (1924, pp. 244, 371) at many points along the coast. They are best developed on the northwestern promontory, where the Bombardopolis plateau bears reef limestones up to altitudes of 1400 feet. According to oral information from the first of these observers, the reef terraces are fairly broad fringes which were formed during pauses in the upheaval of the promontory; and the upheaval appears to have increased the folding of the previously developed promontory anticline, for the reefs gradually decline northeastward and southeastward to sea level.

Summary for Elevated Fringing and Barrier Reefs

The foregoing review of elevated fringing and barrier reefs warrants the formulation of several conclusions. The first concerns sea-level rather than elevated reefs: it is that practically all the shores over which the above-described elevated reefs occur are bordered by fringing reefs. Thus confirmation is found for Darwin's belief that fringing reefs are commonly associated with rising coasts. But, second, these sea-level fringing reefs are, in the large majority of cases, attached to an eroded shore of firm rocks, and the shore line is more or less embayed, or would be if the embayments had not been largely filled with delta plains; hence the rise of these coasts which has favored the growth of their shore reefs is of less measure than a previous subsidence. Had it been of greater measure, a coastal plain of unconsolidated marine sediments would have been laid bare, on which fringing reefs would probably have failed to grow. The case of the southern coast of Java is perhaps of this kind, if it is not one in which the active outwash of detritus is causing a progradation of the shore line.

Third, as far as elevated fringing reefs are concerned, their prevail-

ingly unconformable relation to their foundation shows that their growth may have been associated with pauses in a subsidence which preceded the later upheaval of their coasts and which was too rapid for reef upgrowth, quite as well as with pauses in the later upheaval of the coast. Hence the association of fringing reef formation with rising coasts is less constant than has been generally supposed. But even if the elevated reefs were formed during pauses in subsidence, they still exemplify Darwin's views, which explicitly included the possible formation of fringing reefs during a pause after rapid submergence, presumably due to subsidence, even though no examples of reefs thus formed were known to him.

Fourth, when a single elevated and unconformable reef is found, it may be reasonably supposed to have been formed during a still-stand pause at the close of a rapid subsidence preceding a later elevation; but when a number of unconformable fringes form a series of terraces on a coastal slope, as on Cebú and Negros, Timor and Misima, it is not possible to determine without a knowledge of their structural relations—a knowledge that even close search on the ground may not secure—whether the reefs were formed during pauses in the subsidence of the eroded slope before its upheaval, or during pauses in the upheaval that followed the subsidence, or some during one movement and some during the other. Fifth, the small thickness of most elevated fringing reefs is the result, as has been explained in Chapter II, of the short duration of the still-stand pauses that permitted their formation, whether such pauses occurred during subsidence or upheaval. It has no bearing whatever on the small or great thickness of sea-level barrier reefs and atolls in the open Pacific.

Sixth, it is noteworthy that only two of the above-cited elevated barrier reefs, those of Mangaia and Rurutu, have been as yet well enough studied to demonstrate that the conditions and processes of their origin confirm the postulates of Darwin's theory. They do so in the most convincing manner, and that in spite of the fact that the Mangaia reef occurs in an oceanic area which Darwin marked, properly enough, as characterized today by fringing reefs and as therefore being a region of upheaval. It is also noteworthy that the evidence as to the manner of origin of the Mangaia and the Rurutu reefs is not found in their internal structure, of which little is known; but, as in the case of elevated fringing reefs, wholly in the unconformable relation of the reef mass to the foundation mass. Furthermore, this relation is determined for Mangaia not so much by the discovery of direct contacts of reef limestone with the volcanic rocks beneath them as by the general topographic relations exhibited by the visible forms of the two kinds of rocks.

Seventh, the initial fringing reefs of which barrier and atoll reefs are the grown-up successors need not have been formed, like the majority of the sea-level fringing reefs noted in this chapter, on a shore line determined by the partial emergence of an eroded coast that has previously suffered a greater submergence, but, more simply if not more probably

also, on a shore line determined by the first subsidence of an abraded and eroded coast. Eighth, it is disappointing that not a single elevated barrier reef has yet been found in which the internal structure is sufficiently laid bare by dissection to give fuller demonstration of the processes of its formation than is given by its topographically unconformable contact with the foundation rocks. The several structural parts of such a reef ought, it would seem, to be easily distinguished. If the reef had been formed according to Darwin's theory, for example, a relatively continuous body of heavy-framed corals, largely in place, would mark the growing face of the reef; external to this body, inclined talus layers should prevail; internal to it, a narrower or broader body of reef-rock fragments, large and small, with few corals in place, would mark the reef flats; and farther inward should come the nearly horizontal layers of the fine-textured lagoon beds, which, as the underlying rocks of the island are approached, would merge into fringing reefs or delta deposits. But no such structural section has yet been discovered. Perhaps an elevated barrier on the small Tongan island of Eua, described in the next chapter in connection with an elevated atoll above it, may afford opportunity of discovering reef structure.

Of all the above records, the one that impresses me most is that concerning the Mangaia barrier; for that reef, although occurring in a region that has experienced recent elevation, was nevertheless formed during a preceding subsidence in a manner precisely accordant with the requirements of Darwin's theory. It is hardly imaginable that so wonderfully successful a theory can be wrong; and conversely, it is difficult to conceive that any of the alternative theories, every one of which fails utterly to match the conditions and processes of reef formation recorded in Mangaia, can be right.

CHAPTER XVI

ELEVATED ALMOST-ATOLLS AND ATOLLS

Outline of Inquiry

The object of the following review is twofold. First, to learn whether the elevated almost-atolls and atolls of the coral seas reveal their structure sufficiently to furnish evidence as to the conditions and processes of their origin; second, to learn whether any of them were formed as bank atolls, in the sense of crowning only a part of a nearly level platform, after the fashion of certain atolls in the northern marginal belt of the Pacific, instead of falling off directly to deep water after the fashion of normal atolls in the coral seas.

Elevated Atolls in the Paumotus

The Paumotus or Tuamotus, HO 77, one of the largest groups of atolls in the Pacific, is distributed over an area of about 900 by 200 miles and includes over 50 members. They have been described by many observers, including Beechey (1831), Couthouy (1844), Wilkes (1845), Dana (1849), Ribourt (1878), Cuzent (1884), Agassiz (1903a), and Friederici (1911), all of whom regard some of them as having suffered a slight elevation. Darwin sailed past several of the atolls on the *Beagle*, but wrote little though he must have thought much about them. He saw "several of those most curious rings of coral land, just rising above the water's edge, which have been called Lagoon Islands. . . . From the mast head a wide expanse of smooth water can be seen within the ring. These low, hollow coral islands bear no proportion to the vast ocean out of which they abruptly rise, and it seems wonderful that such weak invaders are not overwhelmed by the all-powerful and never-tiring waves of that great sea miscalled the Pacific" (1840, p. 479). No word of theory is introduced, although these were the first coral reefs seen by Darwin after the germ of his theory had come to his mind on the west coast of South America not long before. Dana called the Paumotus "a vast island cemetery, where each atoll marks the site of a buried island" (1849, p. 134).

Agassiz, who has given by far the fullest account of these islands, explains them as each representing "not the remnant of a modern [uplifted] reef" but the remains of uplifted beds of Tertiary coralliferous limestone, each of "which at one time covered the greater part of the area of the lagoon, portions of which may have been elevated to a considerable height. This limestone was gradually denuded and eroded to the level of the sea" (1903a, p. 16).

Niau, in the northwestern part of the group, is nearly circular in outline and 4 miles in diameter; it has an elevated reef which, according to Agas-

siz (1903a, pp. 64–67, 6 plates), is "solid and unbroken," 25 feet high and about half a mile wide, with a gentle slope toward the lagoon and an abrupt fall to the shore. The "old ledge," as Agassiz calls the elevated reef, is pitted and honeycombed; the lagoon is a shallow salt-water pond, 3½ miles across and 2 or 3 fathoms deep. A fringing-reef flat, 300 or 400 feet wide, borders the western shore but is wanting on the south. On the much larger atoll of Rangiroa, a far northwestern member of the group, HO 85, 47 by from 12 to 17 miles, the "old ledge" is 12 or 14 feet high and 40 or 50 feet wide on the top. Matahiva has its old ledge at a height of 10 or 12 feet; on Apataki and Kanehi it may be of similar height. No other members of the group, many of which Agassiz described in detail, show elevation of so great a measure; a number of them have beaches of recent origin 12 or 15 feet high, but their "old ledge" is usually described as "planed off," without indication of its present altitude but with the tacit assumption that it was once higher. Pinaki or Whitsunday Island is of interest, because a rather unsatisfactory drawing of it by Beechey was reproduced by Darwin (1842, p. 2) as his type of an atoll. Agassiz says it is an exceptional rather than a typical atoll; but its exceptional quality seems to be only an elevation of a few feet.

Agassiz' explanation of the form and origin of these islands, as above cited, is unacceptable on several grounds. The fact that their limestones are coralliferous shows that they must have been formed at a small depth, probably under 30 fathoms. But, if it be assumed that beds of coralliferous limestone of atoll outline were formed a little below sea level and then uplifted to a small altitude above sea level, it would be impossible that reeflike rims should survive while central hollows were eroded, unless the limestone beds were more resistant around their margins than across their centers; and no reason for so specialized a distribution of more and less resistant parts in a sheet of limestone rock has been offered. On the other hand, if formed as atolls and then slightly uplifted, the present forms of the islands are immediately explained.

It is difficult to understand why an observer so experienced with sea-level atolls as Agassiz was, should have preferred an indirect and improbable explanation for the Paumotus instead of a much simpler and more direct one. In any case, the Tertiary age for the "old ledge" of the Paumotus, which he accepted without qualification, is not well determined, because the present-day fauna of the submarine slopes of the raised atolls is not well enough known to establish a standard with which the fossil fauna of the "old ledge" may be compared.

The occurrence of several slightly elevated atolls in the Paumotus has been taken to imply that a large area of ocean bottom has been uplifted with a near approach to uniformity, or else that the ocean level has fallen; and thus we revert to the suggestion made by Darwin when he wrote of the emergence of this group: "The question will arise, seeing how immense an area has been thus affected, whether those geologists are not

right who believe that the level of the ocean is subject to secular changes from astronomical causes" (1874, p. 171). But Agassiz' detailed records show that the elevation of the islands is not uniform. The highest one, Niau, is nearest to the much higher island of Aurora or Makatea, which stands apart somewhat to the west of the group and is next to be described. All the others are lower, and many of them are so low that Agassiz gave no statement of their height, apart from that of their storm-

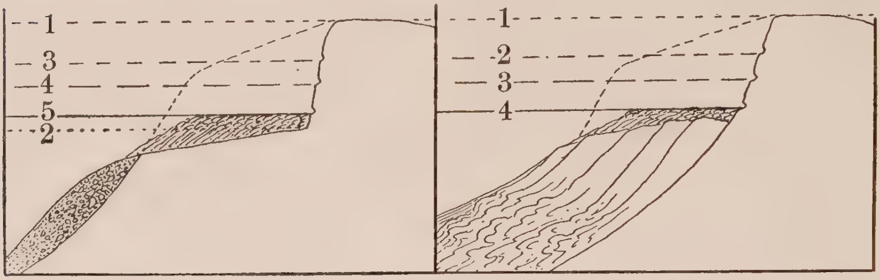


FIG. 197—Diagrams explanatory of cliffs on Aurora Island.

wave beaches. Moreover, he notes explicitly that Niau and Rangiroa are the high members of the group and that many others, a number of which are well to the southeast, are low. Whatever movement has taken place here would thus seem to be of a small and varying measure, with a probable increase westward to Aurora and then a decrease; for most of the Society islands, farther west still, show signs of subsidence and not of uplift. In any case the uplifted members of the Paumotu group have not yielded any clear evidence of the manner of their formation.

Elevated Atolls between the Paumotus and Tonga

Aurora, also known as Makatea, a generic name meaning elevated reef, stands southwest of the Paumotu group, HO 83, 4½ by 1½ miles, and has the form of a crescent with the horns to the northeast. It is exceptional for its region in having the considerable height of 230 feet. According to Agassiz (1903a, pp. 56–64, 15 plates) this limestone island is boldly cliffed on the west, north, and east but slopes with two distinct terraces to the south. A central depression in the island is from 50 to 75 feet lower than the rim. The surface is everywhere pitted and honeycombed and shows "spires and pinnacles, or huge masses forming indistinct cyclopean walls alternating with deep crevasses, small caverns and potholes." Agassiz interprets the central depression as the work of atmospheric agencies after elevation; Dana had earlier regarded it as preserving the form of a preëlevation lagoon. The uplands have been worked for lime phosphate. A reef flat surrounds the island, but it is apparently in part at least an abraded platform from 200 to 400 feet wide with corals and other organisms growing on it.

Horizontal lines of cornices, five or six in number, in the cliff face are taken to indicate wave work during as many pauses in the elevation of the island; but, if so, the cliff face must have existed prior to the elevation; for it is hardly conceivable that the initial submarine slope and pitch of the rising island could have been cut back in platforms at lower and lower levels so systematically that all the cliffs at the back of the platforms should now unite in a single cliff, marked only by slightly excavated cornices at the platform levels, as in the right half of Figure 197. If the cliffs are truly the work of abrasion, they should have been cut, once for all, when the island was somewhat more elevated than now, at level 2 in the left half of Figure 197; then, as the island was submerged and reëlevated with brief pauses, the cornices should have been cut during fall or rise at the levels 3, 4, 5.

But another origin for cliffs of this kind has been suggested by Gardiner, who noted that the faces of certain elevated atolls in Fiji are much steeper than the submarine slopes of non-elevated atolls and who therefore suggested that such cliffs "can only be accounted for by the splitting off of great masses of the rock" (1898, p. 470) during or after elevation, in the fashion of landslides. If the cliffs of Aurora have been produced in this way, the successive cornices may have been cut in the cliff face during pauses in a first emergence after the slides had taken place.

Henderson or Elizabeth (not to be confused with the Elizabeth bank-atoll in the marginal belt east of Australia), southeast of the Paumotus, HO 1977, 5 by 2½ miles, about 100 feet high, with cliffs 40 or 50 feet high, is one of the southernmost atolls of the Pacific, lying in latitude 24° S. Its shore is bordered by a discontinuous fringing reef.

Niue or Savage, east of the Tonga group, HO 1986, about 13 by 10 miles, 200 to 250 feet high, is, like its fellows elsewhere, of simple aspect. Its low and level outline is 200 times as long as it is high. It has been described in a general way by many visitors, among whom Hood (1863), Goodenough (1876), Moss (1889), Tregear and Williams (1893), S. P. Smith (1902–03), Thomson (1902), and Agassiz (1903a, p. 171, 8 plates) may be named. The island is composed wholly of limestone, covered by a thin reddish soil. The rim of the island rises 60 feet or more above a broad interior depression; the outer slope of the rim is benched at several levels and cliffed around part of its shore, where a discontinuous fringing reef has been formed; the reef is extended seaward for nearly half a mile by a flat of coral sand. Small canyons have been cut back from the lower bench into the rim slope; nothing is known of the structures revealed in the canyon walls.

Elevated Atolls in Tonga

Eua and Its Elevated Reefs

Eua, the small, southeasternmost member of the Tonga group, HO 2010, 10 by 4 miles, has a limestone crest which attains the excep-

tional height of 1078 feet; it is therefore the loftiest elevated reef in the open Pacific; Vatu Vará in Fiji comes next, with a height of 1030 feet. Eua has been briefly described by Oldham (1890) and more fully by Lister (1891) and Agassiz (1903a, pp. 180–187, 8 plates); it is thus known to have a base consisting of volcanic rocks, mostly bedded tuffs. It falls off in a steep face (Fig. 198) to the east, as if about half of the original island had there been lost by downfaulting. The western slope is gentler; here

FIG. 198—Profile of Eua, modified from Lister's section (1891, p. 601).

several limestone terraces are seen. The largest one of these, as shown on Lister's map, stands out somewhat below half height of the island and occupies nearly half the island area; it has a higher margin enclosing a shallow depression in the northern part of its length and thus simulates a barrier reef of long continued and slow upgrowth. The terrace margin is 440 feet high at the south, 325 in the middle, and 270 at the north, thus suggesting a gentle northward tilting; and this agrees with the tilting of Tongatabu, the much larger limestone island of southern Tonga, as will be seen in the next section.

At higher levels, several narrow terraces appear to represent fringing reefs formed after rapid movements of small measure; but the highest terrace forming the crest of the island represents a long narrow atoll or so much of an atoll as has not been lost by downfaulting on the east. The upper limestones are much eroded; Lister described them as remaining "sometimes in large projecting masses . . . sometimes weathered down into groups of isolated pinnacles standing on the volcanic basis"; he recognized that the contacts thus revealed are unconformable and inferred that "the [volcanic] mound was elevated above the [sea] surface, considerably denuded, and afterwards depressed to such a depth, at least, as to submerge its summit. A covering of calcareous organisms was deposited on the volcanic basis while it was submerged" (1891, p. 606). Agassiz stated that dikes of intrusive rock "cut through the volcanic deposits but do not enter the overlying calcareous strata" (1903a, p. 187); but, instead of interpreting this significant observation as showing that the limestones were deposited during a submergence that followed the eruption and degradation of the volcanic rocks, he seems to have regarded the volcanic eruptions of later date than the limestones, for he wrote: "The present topography of Eua indicates that at one time it must have been a large flat limestone plateau . . . pushed up by volcanic outbursts on the east coast, which was little by little disintegrated according to the hardness of the various terraces" (p. 187).

Inasmuch as the supposed barrier reef on the western side of the island appears to have begun its growth on the subsiding island near the present base of the island slope, the eroded surface of the volcanic rocks may descend somewhat lower still; and in that case the total subsidence of the eroded island must have been at least 1000 feet during the formation of its reef terraces. It may therefore be inferred that the barrier reef would have grown up in a single reef of that thickness, had not the later phases of the subsidence been accelerated. Inasmuch as the upper fringing reefs appear to have been successively drowned by the impulses of subsidence which then took place, it is eminently possible that the culminating atoll also was in its turn drowned before the subsidence was reversed into the upheaval by which the reef-benched island was given its present altitude. Although incompletely studied, Eua is already one of the most instructive reef-bearing islands in the Pacific coral seas. Darwin colored it red on his chart, to indicate that it has been fringed with a sea-level reef after its elevation; he would surely have been glad to know the evidence now forthcoming to show that, before elevation, it had subsided and become reef-terraced and atoll-crowned.

Tongatabu and Vavau

The larger limestone islands of Tongatabu and Vavau at the southern and northern ends of the Tonga group, HO 2016, appear to be unsymmetrically formed atolls, each one obliquely upslanted while the area between them was gently depressed. No foundation rocks are mentioned in the accounts of the islands by Studer (1877), Lister (1891), or Agassiz (1903a, pp. 175–203, 22 plates). Each island forms the elevated margin of a good-sized bank, which seems to represent the submerged part of the slanted atoll. Two larger banks lie between the islands, the over-all length of the whole group being 160 miles.

Tongatabu, HO 2016, the chief southern member of the group, has a bold face, convex to the south, about 20 miles in curved length, and 270 feet high at the highest, with a gradual slope to an irregular northern shore line. Vavau, HO 2012, is smaller but higher; its bold and irregular northern face, 10 miles in curved length, has a notably even crest, half a mile or less in width, 550 to 670 feet high on the northwest, decreasing in height to its southern ends. The decrease of height is continued in detached islands by which the irregular curve of the northern face is continued, to the south on the east and to the southwest on the west, to a total length of nearly 20 miles. Unlike the exterior cliff the interior slope of the island is more gradual; it is interrupted by a number of branching bays between branching spurs. In the absence of local studies concerning structural details the interpretation of these two islands as upslanted atolls is only tentative. They are at present less instructive than little Eua.

A number of raised atolls of small size occur in association with the

Namuka and Haapai banks, between Tongatabu and Vavau, HO 2006, 2007, 2008 (Fig. 217). The Haapai bank bears nine of these, a mile or less in diameter and from 50 to 200 feet high; some of them rise directly from the bank and have fringing reefs around their shores; others rise from lagoons, two or three miles across, enclosed by sea-level reefs which rise from the bank; still others rise from areas adjoining the bank with depths of 200 fathoms or more. They all appear to have grown up during phases of the subsidence by which the banks gained their former considerable depth, although Lister concluded that "there is no need to call on the hypothesis of subsidence to explain their form" (1891, p. 616). The atolls are therefore of a later generation than the limestone islands of Tongatabu and Vavau, the uplift of which presumably took place when the banks subsided. The fact that the little atolls on the banks are now emerged indicates that the banks, which will be described in Chapter XVII, have been moderately upraised since their subsidence. Before that upraising, when the now elevated atolls were at sea level, the banks must have been deeper than at present.

Elevated Atolls in the Phoenix Group

The slightly elevated atolls of the Phoenix group, about 700 miles north of Samoa and next south of the equator, are eight in number; they are scattered over an area 200 miles east-west by 100 north-south, as follows:

Name	HO	Diam. (Miles)	Height (Feet)	Name	HO	Diam. (Miles)	Height (Feet)
Gardiner . . .	125	3	40–50	Sidney	125	2	30
McKean	125	1	15	Phoenix	1211	½	18
Canton	1211	8 by 2	20	Birnie	125	1	6
Enderbury . . .	125	3 by 1	25	Hull	125	5 by 2	0

The small inequality of altitudes among these islands suggests that their elevation is due to a broad and nearly uniform upheaval of the sea floor. This inference is of interest in connection with the Paumotus, already described, and also with the drowned atolls of the Darwin Hermatopelago, to be described in Chapter XVII, where some 24 atolls scattered through a large area west of Samoa and north of Fiji have been rather uniformly submerged. The small size of the Phoenix atolls has frequently been explained by those who accept Darwin's theory as indicating a diminution of formerly larger atolls by inslanting upgrowth during prolonged subsidence. If this be true, it is likely that some members of the group, after being reduced to mere pinnacles, have been submerged. A search for lost atolls hereabouts in vessels equipped with the newly devised echo-sounding apparatus would be of special interest in oceanic exploration. Submerged reefs are also expectable in the broad blank space between the Phoenix group and the Hawaiian chain.

Elevated Atolls in the Western Pacific

Ocean or Banaba Island, west of the Gilbert group—not to be confused with Ocean or Kure atoll, the northwesternmost member of the long Hawaiian chain—HO 2179, 2 miles in diameter, 265 feet high, has, according to Power (1902) and Owen (1923), a nearly flat upland of limestone, the exterior slope of which falls off in a shore bluff from 12 to 30 feet high; the bluff is fronted by a narrow fringing reef. The limestone body of this island is capped with phosphate rock, estimated by Cowper-Read (1903) at over 12,000,000 tons.

Nauru or Pleasant Island, an isolated raised atoll west of the Gilbert group and northeast of the Solomons, HO 2179, about 3 miles in diameter and 210 feet high, has been described by Senfft (1896), Krämer (1898, 1906), Power (1902), Hernsheim (1903), Elschner (1913), and Hambruch (1914). It has been much worked for phosphate rock. The raised reef rim seems to be little eroded; a central depression, the floor of which is but little above sea level, represents the original lagoon, which must have been of normal depth. A low exterior belt a few hundred feet in width is bordered by a 600-foot fringing reef. Senfft records that the island consists mostly of bedded "Korallenkalk, der schichtenweise aufeinander gelagert ist; einzelne Lagern zeigen eine gelblich weisse Farbe, ähnlich der des alten Elfenbeine, sind sehr hart, glänzend und nicht porös." This would seem to be a lagoon deposit. Hambruch concludes that the reef was formed by upgrowths during subsidence before its recent elevation but presents no convincing evidence to support his opinion.

Feis, HO 1756, in the western part of the Caroline group, a mile and a half by half a mile, 65 feet high, is described by Prowazek (1913) as composed of limestone with a fringing reef around the shore. Angaur, HO 5423, the southernmost member of the Pelew group, 6 miles south of the Babeltop barrier reef, is an elevated atoll 1 by 2 miles in diameter and 200 feet high on the west side; it is worked for lime phosphate. The Borodino Islands, HO 5349, east of Okinawa in the Riu-kiu curve, are small elevated atolls, 3 and 2 miles in diameter, with an upland rim 200 feet in height, a central hollow, and cliffed sides. A quarter-mile bank surrounds them. Rasa, not far away, shown on the same chart, ¾ mile in diameter, is of similar form, 100 feet high.

Guam, CS 4202, 27 by 4 to 8 miles, is in large part a plateau of coral limestone, from 350 to 500 feet in height, overtopped by several well dissected volcanic summits, especially along the western side of its southern half, up to 1290 feet altitude. Agassiz gives several half-tone views of this island and describes its steep sides as generally marked with terraces, some of which are formed "by the gradual sloughing off of the lower parts" (1903a, pp. 366–376). This gives some warrant for Gardiner's suggestion above quoted, as to the origin of the steep faces of

emerged atolls. Agassiz also describes one of the volcanic masses on Guam as having burst through the limestones and now rising 200 feet above them. Cox describes the volcanic rocks as older than the limestones (1904, p. 387), but without detailed evidence.

Safford writes: "All of the mountain peaks of Guam are undoubtedly of volcanic origin. . . . Surrounding the bases of the mountains are ancient coral reefs, the margins of which, in contact with the volcanic products, have in many places been converted into crystalline limestone, showing evidence of volcanic activity after the whole island had been raised from the sea. . . . The entire northern portion of the island is a raised coral platform penetrated in several places by the low volcanic peaks. On the west side of the island . . . several distinct flat terraces occur, showing successive upheavals" (1905, p. 51). The possibility that some or all of the volcanic masses are older than the limestones does not seem to be excluded, in spite of the mention of crystalline limestone; for such limestone is found abundantly in upraised reefs where no signs of volcanic activity are present. The later date of the volcanic knobs than of the reef limestones is made improbable by the absence of lava flows superposed on the limestone of the upland. In the absence of a critical discussion of the relative age of the volcanic and limestone rocks, Guam may be provisionally regarded as an elevated almost-atoll.

The shores of Guam are rimmed by a discontinuous fringing reef up to half a mile in width; but at the mid-west coast the reef runs offshore as a barrier, meeting a slender peninsula and enclosing a lagoon 1 or 2 miles wide and 28 fathoms deep. Two submarine banks stand 15 and 30 miles south of the island: Galvez, of discontinuous outline, 8 by 4 miles over all, and 15 to 31 fathoms deep, and Santa Rosa, 4 miles across, 3 to 9 fathoms deep. The condition of these banks when the limestone plateau of Guam lay at sea level offers an interesting field for speculation.

Elevated Atolls in Eastern Fiji

The Lau or eastern division of the Fiji group, HO 2851, 2852 (Fig. 137), contains a good number of elevated limestone islands in various stages of dissection and degradation. They have been described by Moore (1897), Gardiner (1898), Agassiz (1899, 1903a), Andrews (1900), and Foye (1918). The second of these observers confidently regarded the less dissected islands as elevated atolls; he concluded that, in view of their peculiar rim-and-basin form, "it is impossible to conceive that they can have any origin different to that of many of the atoll, barrier and fringing reefs of the present day" (1898, p. 467); Moore was of the same opinion (1897, p. 463). It was in connection with some of these islands which have precipitous slopes that Gardiner suggested, as already quoted in the account of Aurora Island, the occurrence of marginal landslides (1898, p. 470). Foye is less emphatic regarding the origin of the islands as

atolls but inclines to that view. Agassiz regarded them not as atolls at all but as elevated and irregularly eroded masses of Tertiary coralliferous limestone (1903a, p. 206) and explained the lagoon-like central depressions which characterize the least eroded of them as "similar to the gigantic banana holes, as they are called, occurring in the Bahamas" and as "due to the action of atmospheric agencies" (1899, p. 53), thus repeating his interpretation of the Paumotus. Inasmuch as the least eroded of these islands, like other little-eroded limestone islands elsewhere in the coral seas, have essentially the shape that uplifted atolls ought to have, while uplifted limestone masses of other origin would not have that shape, Gardiner's view seems to be the correct one and is here adopted.

The Kambara Belt of Nine Elevated Atolls

The highest limestone island in Fiji, exceeded in height only by Eua in the open Pacific, is little Vatu Vará in the east-center of the group. It is 1½ miles in diameter and 1030 feet in altitude; a half-mile fringing reef rims its southwestern shore. Its top is nearly level, its upper slopes are precipitous; its upheaval must have been recent and rapid, for according to Andrews (1900, p. 31) it still bears corniced shore lines at heights of 800, 600 or 700, 350, 25, and 15 feet.

Yathata, 9 miles north of Vatu Vará, 2½ by 1½ miles, 840 feet high, rimmed with a good sea-level fringe, is adjoined on the east by the smaller island, Kaimbu, 2 miles long, 150 feet high. Both islands are, according to Agassiz, composed of limestone. The larger one is described by Andrews as showing on its western side "a volcanic mass that has welled up to the 500 feet level, scorching and whitening the limestone" (1900, p. 22); but, as this brief statement is not accompanied by details, especially regarding lava contacts, further examination is desirable to determine more surely whether the limestones lie conformably on a non-eroded and therefore never-emerged volcanic cone, unconformably on an eroded and hence for-a-time emerged cone, or whether the volcanic rocks have actually been intruded into the limestones, as above stated.

Andrews also noted that, although the "truncated sugar loafs" of Vatu Vará and Yathata, which he took to be raised atolls, are weathered to blades and needles, their mass "still marvelously preserves the original contour of the reef as it rose from the waters" (1900, p. 29); but Agassiz, who had engaged Andrews to examine the limestone islands in Fiji, adds a footnote: "I think Mr. Andrews is mistaken. The immense amount of denudation which has taken place in the Fiji islands and other elevated reef islands in the Pacific I have examined, shows that the original reef slope is not preserved to any extent. It has usually been greatly obliterated by denudation and erosion." This seems to me to treat the Fiji islands in too uniform a manner; for nothing can be clearer than that divers movements of elevation and of subsidence varying in date and

amount have taken place there and that, while some elevated islands are little modified by erosion—witness the several lines of corniced shore lines that Andrews records on Vatu Vará—others have been almost demolished, as will be more fully shown in the following pages.

Forty miles to the southeast of Vatu Vará is Naiau, 3 by 2 miles, somewhat east of the belt to which it belongs. According to Agassiz it is "composed entirely of an elevated limestone ridge forming a continuous rim around a central depression stated to be about 200 feet lower than its highest points, which rise from 530 to 580 feet above the level of the sea" (1899, p. 52). The rim descends by a steep exterior slope at first but with a gentler declivity below. The shore is fronted by a half-mile fringing-reef flat. Moore has suggested that a boring in the central depression of this island would probably discover buried volcanic rock not far below the surface (1897, p. 463), thus implying his acceptance of Darwin's theory in explanation of atolls but without giving reasons for the small depth of burial inferred for the reef foundation.

Vanua Vatu lies 25 miles southwest of Naiau; it is 1½ miles in diameter with a rim 310 feet high enclosing a central depression. This island is unlike its fellows in this belt in being encircled by a narrow and close-set barrier reef instead of by a fringing reef.

Kambara, 60 miles south of Naiau, 5 by 3 miles, has a somewhat eroded limestone rim 300 to 350 feet high enclosing a central depression, from the floor of which, 100 feet above the sea, rise many steep-sided limestone hills nearly to the rim level; a half-mile fringing reef borders the shore. The northwest part of the rim is, according to Agassiz, "broken through by a conical hill 470 feet high, which is of volcanic origin" and which is regarded by Gardiner and Foye as intrusive in the limestone. Wangava, a smaller island near by on the northeast, 3 miles by 1 mile, has a rim nearly 300 feet high and a rather broad fringing reef. Foye notes that "Kambara was formed by subsidence" but without giving specific reasons for his belief; also that both Kambara and Wangava are cut off by a fault along the northwest side (1918, pp. 66, 68), thus independently coming to the same conclusion that Gardiner had reached for the steep faces of other raised atolls.

Fulanga (Fig. 208), in the southeastern part of the Fiji group and 20 miles southeast of Kambara, 5 by 3 miles, rimmed with a sea-level fringe, has been described by Gardiner (1898, p. 457), Agassiz (1899, p. 62, Pls. 83, 84), and Foye (1918, p. 74) as consisting wholly of limestone. Its even-crested atoll-like rim, reaching heights of 240 to 260 feet on the west, slopes according to Agassiz (1899, p. 69) gently to the east; it is breached at several points on the northeast. The central depression is occupied by a lagoon, 5 or 10 fathoms deep, interrupted by many limestone islands, thus suggesting that a formerly even lagoon floor was well dissected during a somewhat greater emergence than now, perhaps during the last Glacial epoch. Moore regarded this island as mark-

ing an "extinct crater" (1889, p. 203), but as no volcanic rock has been observed in it by any of several observers, including Moore himself, his opinion is little more than an unconfirmed supposition.

Agassiz explained Fulanga as "a bed of raised coralliferous limestone," thus implying that it originally had a level surface, and ascribed its elevation to "volcanic agencies"; he described the central depression as "studded with innumerable islets and rocks. . . . This atoll-like basin has thus in reality been formed by the wearing action of the sea, and subsidence has played no part in its formation" (1899, pp. 63, 64). The objections to this view stated for the Paumotus hold here also; for no reason is given to show why a bed of limestone should have a central basin excavated in it by the sea, while its fairly even rim remains so little degraded. Elevation by volcanic agencies is altogether improbable.

All the above-described elevated and little-dissected atolls are fringed with sea-level reefs, except that Vanua Vatu has a narrow, close-set barrier reef, thus supporting Darwin's view that fringes are commonly associated with rising coasts. Furthermore, all the islands lie in a narrow belt, 150 miles in length, trending south-southeast; except that Naiau and Fulanga lie a little out of line to the east. The belt may be named after the island of Kambara. The decrease of height from Vatu Vará to Yathata leads, 28 miles farther north-northwest to the sea-level barrier reef around Ngamia and Lauthala, already described with other barrier-reef islands of central Fiji as indicating subsidence: hence the movement of upheaval must have decreased rapidly in that direction. In the other direction the decrease of elevation is for the most part more gradual.

Extinguished and Resurgent Reefs

A brief excursion may be here made to one side of the line of inquiry in hand, in order to explain the occurrence of several small resurgent reefs in association with the above-described belt of elevated atolls. Theoretical considerations, more fully stated in one of my earlier articles (1916b), lead to the expectation that upgrowing reefs around a subsiding island in a deep ocean should be constructed with an inward slant. The chief ground of this expectation is the economy that such a style of construction permits with respect to the expenditure of reef detritus for the progradation of the long, submarine reef talus that pitches down to the deep ocean floor. Furthermore, in an ocean of a given depth small reefs should have a more pronounced inslant than large reefs, because the smaller the reef circuit the greater the amount of detritus for talus progradation that must be provided by a unit length of growing reef face.

If the inslant angle be thus increased to 45°, which does not seem excessive for atolls a mile or less in diameter in water 1000 or 1500 fathoms deep —like the dangerous little Horseshoe atoll in the central Koro Sea of the Fiji group—the atolls will be reduced to mere pinnacles by a further sub-

mergence of 400 fathoms. Thereafter, as the vertical upgrowth of such pinnacles will render them liable to overturning by storm waves, they cannot maintain themselves at sea level but will be extinguished by toppling over, even though subsidence be relatively slow. Hence, small reefs thus extinguished should not be confused with large reefs that are drowned by rapid subsidence. After a little reef has been extinguished, it may be brought up to or above sea level again by upheaval; and it may then be described as resurgent. On nearing and reaching the sea surface, its size may be increased by new-made fringing reefs.

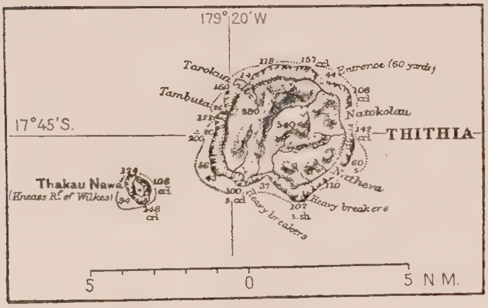


Fig. 199—Thithia, Fiji; HO 2852.

The following examples of resurgent reefs, known to be such because they lie near elevated atolls, may be cited. A few miles west of Yathata lie the small, sea-level Nukutolu reefs, probably enlarged since their resurgence by the growth of new fringes. Nearly midway between high-standing Kambara and Vanua Vatu stands the lower islet of Tavunasithi, half a mile in diameter at the base, 200 feet high, and rimmed with new fringing reefs. As the neighboring larger islands both stand higher than 300 feet, it is probable that, when their reefs were at sea level, little Tavunasithi was completely submerged; it must have been extinguished when its reef top was reduced to a mere peak and could no longer support the higher upgrowth which the larger reefs of Kambara and Vanua Vatu continued to enjoy. Morambo, a third way between Wangava and Fulanga, a mile in diameter, and 160 feet high, would seem to have had a similar history. Other examples, all of small size, are two reefs between Naiau and Tuvuthá; Nawa reef, next west of Thithia (Fig. 199); and Frost reef, between Vatu Vará and Mango (Fig. 201).

It is noteworthy that no atolls 2 or 3 miles or more in diameter lie at sea level in the Kambara belt of high-standing atolls above described. If such were found, they also would have been submerged when the now high-standing islands were at sea level; and their submergence, not being ascribable to extinction by inslanting upgrowth because of their good size, could have been caused only by rapid subsidence; but the high-standing atolls testify against rapid subsidence. The absence of such sea-level atolls solves this quandary.

Raised Reefs on Two Caldera-like Islands

Two caldera-like islands, Thithia and Mango, each bearing elevated reefs, occur in association with the preceding nine elevated atolls of the

Kambara belt and may be taken, if any reader is so inclined, to support Moore's suggestion, just quoted, that Fulanga is based on an "extinct crater." Totoya, already described with the sea-level barrier-reef islands of central Fiji, may also be assumed to support the same view; but the prevalence of well-dissected volcanic islands and the rarity of young crater or caldera islands in Fiji suggest that Fulanga and its companions more

FIG. 200 a and b—Elevated and dissected fringing reefs, northwest coast of Thithia, Fiji.

probably owe their pattern to the upgrowth of reefs that began, as in the case of the Totoya barrier itself, in fringes on island shores—whether the islands rose in caldera rings or not is immaterial—than in fringes that were initially perched on caldera rims. Moreover, the initial perching of fringes on caldera rims requires that the rims should have been built up to rather narrowly limited depths below sea level; and that is improbable, as Darwin long ago made clear. The discussion of this matter in connection with the caldera ring of Niuafou in Chapter X should be here recalled.

Thithia (Fig. 199), a little more than halfway between Vatu Vará and Naiau, 4 miles in diameter, consists of a fairly even ring of volcanic hills 450 feet high with a hilly central depression; it therefore appears to represent a dissected caldera island. The outer slopes bear a number of reef-limestone patches, as in Figure 200, up to heights of about 300 feet. Andrews records that one part of the shore rises in a limestone cliff 2 miles long, with its face sloping 50° or 60°, and that the cliff face is interrupted where "a huge block of some 20,000 tons . . . has slipped down slightly," so that if it should descend farther it "would expose a cliff 100 feet in height"; he adds that "the precipices occupying the upper 300 feet of Vatu Vará may have been formed similarly" (1900, p. 29), thus repeating Gardiner's landslide idea. Andrews' opinion as to the origin of Thithia was that it formerly "possessed an outer ring of raised coralline limestone origin, with a central hollow"—that is, it was an elevated atoll—but that the "hollow has been so encroached upon by lava outbursts that there is at present but a hint of its former extent." The limestones "project but

slightly through the down-like slopes of lava," and only "four or five bold black cliffs" now represent the "old limestone ring" (1900, p. 20). The brief visit that I made to this island gave me a different impression of its history: I took it to be, as above noted, a dissected caldera island on which a discontinuous fringing-reef ring was formed during subsidence.

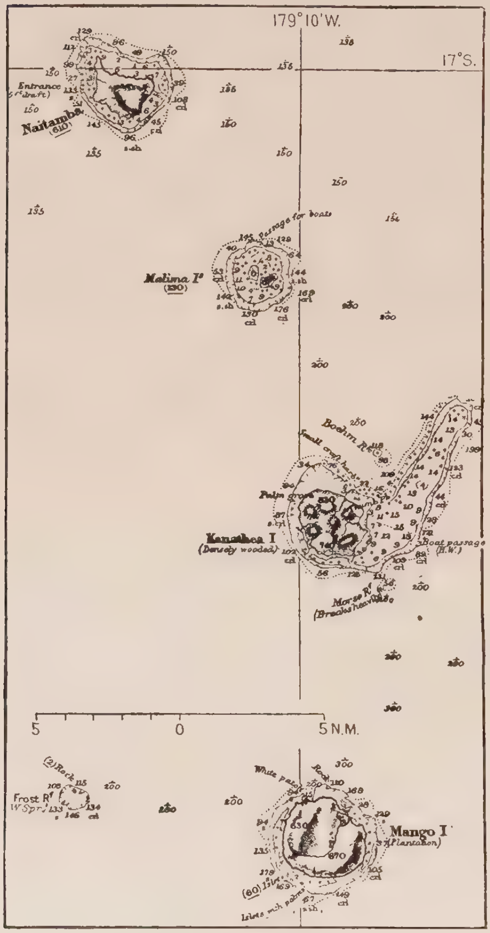


FIG. 201—Mango and neighboring islands, Fiji; HO 2851.

Mango (Fig. 201), 20 miles east of Vatu Vará, is a ring of volcanic hills, 3 miles in diameter and 670 feet in greatest height, around a central depression. The hill ring bears on its outer slope a discontinuous rim of elevated reef limestones 400 or 450 feet in altitude and is surrounded by a sea-level fringing reef of moderate width. This island was rather closely studied by Andrews in 1899; its inferred structure is illustrated by several cross sections in his report (1900, Pl. 2), in which the more recent volcanic rocks, as well as the rim of reef limestones through which the recent volcanics are thought to have broken, are represented as resting upon an evenly truncated platform of older and inclined volcanic conglomerates; but the truncated platform is drawn as standing below sea level, and its existence must therefore be wholly a matter of inference for which, as noted in Chapter X, the observations recorded in the text give no sufficient warrant.

Some recent volcanic action truly seems to have taken place, for a thin intrusive lava sheet was noted in the limestones near the point where I landed on this island; but a later origin for the large ring of volcanic rocks than for the elevated rim of reef limestones (Fig. 202), which rests rather evenly on the outer slope of the volcanic ring, seemed to me improbable; for the reef rim, although very likely much reduced from its original breadth by landslides and perhaps also by erosion, pre-

serves a fairly uniform altitude along considerable distances. Moreover, the ring of volcanic rocks appeared to have been maturely dissected before the now-elevated limestone rim was deposited, apparently in unconformable relation, upon it. At the close of the few hours that I spent on Thithia and Mango, where as many days would have been none too long a time for their proper study, I felt the truth of Darwin's experience: "It is the fate of every voyager, when he has just discovered what

FIG. 202—Ideal section of Mango, Fiji.

object in any place is more particularly worthy of his attention, to be hurried from it" (1840, p. 475).

Sherlock, studying specimens collected by Andrews, reports that a rock from a height of 310 feet on Mango contains *Orbitoides sumatrensis*, which is of Miocene age (1903, p. 351); but, if so, the island must have been about stationary through Pliocene and much of Pleistocene time, for the amount of erosion that it has suffered since elevation is moderate. A later date would accord better with the physiographic history of this island as well as with that of Mangaia already mentioned and of Uvea yet to be mentioned. Kanathea (Fig. 201), not far northeast of Mango, may be mentioned here. The passing view that I had of it disclosed what I took to be an elevated reef remnant on its volcanic slopes; but Foye, who ascended to its summit found no elevated reef; its position in the present problem is therefore uncertain.

The Elevated Atoll of Tuvuthá and Its Volcanic Foundation

Tuvuthá, 40 miles east-southeast of Vatu Vará, 27 miles east of Thithia, and 20 miles northeast of Naiau, 3 by 2 miles and 800 feet high, is unlike all but one of the nine elevated atolls of the Kambara belt above described in being encircled by a barrier reef which encloses a half-mile lagoon instead of by a fringing reef. The island consists mostly of limestone; its fairly even circular crest encloses a high-level central depression; the exterior slope falls off to the sea in steep bluffs.

Agassiz noted that the west side of the island has been "greatly denuded and eroded into rounded peaks and domes"; he saw no volcanic rock but assumed its presence within the body of the limestone mass, as follows: "The central volcanic mass which has elevated Tuvuthá as well as Naiau has not broken through the elevated limestones . . . the formation of the central basin is not due to volcanic agencies, but to atmospheric causes" (1899, p. 51). Andrews' section of Tuvuthá (1900, Pl. 3) shows the limestone mass resting upon an even floor of volcanic rocks,

like the floors drawn in his section of Mango and Thithia, but again without observational warrant.

Foye ascended the slopes of Tuvuthá and saw that the limestone crest, 800 feet high and somewhat eroded into weird forms, encloses a "circular moat," inside of which a ridge of volcanic rock rises to 540 feet above sea level. He then made the capital discovery that the dissected limestones lie on the volcanic mass in such a manner as to show that the surface of the latter undulates "in low rolling hills" of subaerial erosion, and he therefore concluded that the contact between the two rock masses is unconformable. Hence the volcanic rocks are not intrusive into the limestones, and the upheaval of the island is not due to volcanic action. Foye further states that "Tuvuthá, like Thikombia-i-lau [one of the Exploring Isles to be described below], was formed by the mature erosion of an isolated volcanic peak. It was then submerged, overlaid by limestone, and uplifted." Hence this island has clearly had a two-phase history. The depth to which the unconformable contact extends was not determinable. It is also noted that "coral heads in place appear from top to bottom of the 590 feet of limestone; and in such relations that subsidence is the most logical explanation of their position" (1918, pp. 56–58). It might have been added that the subsidence must have been fairly slow, as it was so well compensated by upgrowth, and yet so fast that not enough detritus was deposited upon the exterior submarine slope to conceal the coral heads.

Tuvuthá thus appears to be one of the most competent witnesses as to the conditions of atoll formation that has ever been summoned before the court of scientific inquiry. Without regard to this or that theory of reef origin that it may support, this raised atoll will be taken as a guide to the formation of other atolls either elevated or at sea level in eastern Fiji, which show no volcanic rock. Thus guided, we may conclude that the nine elevated atolls of the Kambara belt have, like Tuvuthá, had a two-phase history: namely a subsidence during the production of their ring-and-basin form and an upheaval by which they were recently given their present elevated position.

The Ongea Belt of Elevated and Dissected Atolls in Eastern Fiji

About 20 miles east of the Kambara belt of elevated, little-dissected atolls above described, is another belt—the Ongea belt—of elevated and much dissected limestone islands, some of which show their volcanic foundations. All of them are believed, for reasons given below, to have been formed as sea-level atolls or almost-atolls before their dissection was initiated by upheaval. The larger ones now have embayed shore lines; and all of them are now surrounded by sea-level, lagoon-enclosing barrier reefs, as if the central dissected islands had been moderately submerged

after the dissection that followed their upheaval was well advanced. Some of the sea-level reefs here occurring might have been described in an earlier chapter as almost-atoll reefs, for their central islands are mere pinnacles of limestone or volcanic rock. A number of small sea-level atolls occur in connection with this belt of elevated and dissected reefs, on which certain significant inferences will be based in a later section.

The Exploring Isles

The Exploring Isles (Fig. 203), so named by the U. S. Exploring Expedition under Wilkes, are five in number and stand about 30 miles east of Vatu Vará and Yathata. They are composed of volcanic rocks and unconformable overlying limestones and are all enclosed by a fine barrier reef, measuring 25 by 15 miles. The largest of the Isles is Vanua Mbalavu, close to the western arc of the reef circuit, with a bent length of 14 miles and a width of from 1 to 3; it is a slender chain of maturely degraded volcanic hills (Fig. 204), 930 feet in greatest height, unconformably overlapped, chiefly on its northwestern side, up to a maximum height of about 600 feet, by limestones, now dissected into an extremely ragged surface and well embayed.

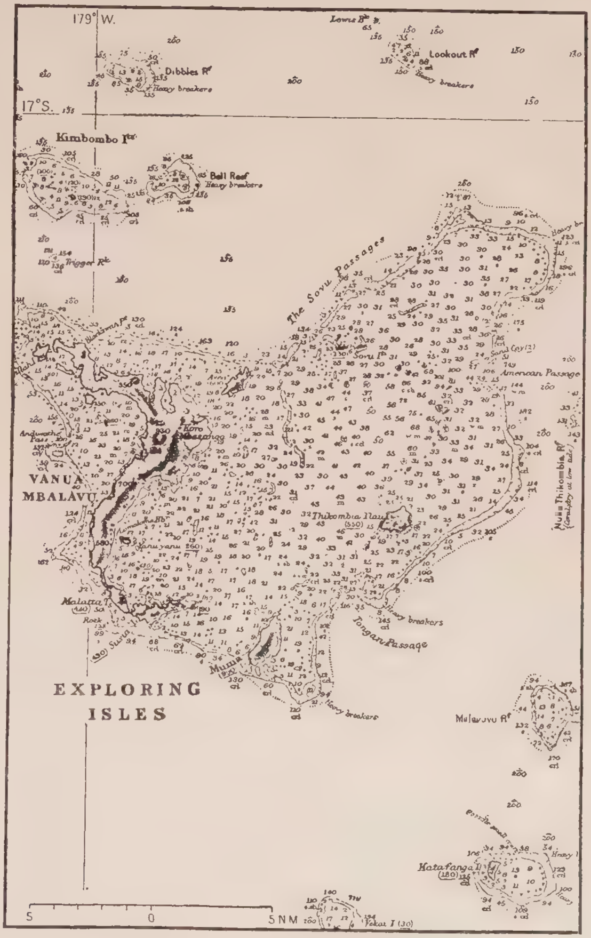


FIG. 203—The Exploring Isles and their barrier reef, Fiji; HO 2851.

During the brief inspection of the Exploring Isles that I had opportunity of making in 1914, a two-day hurricane compelled the trading steamer that carried me through northeastern Fiji to take refuge in one of the bays which indent the residual limestone cover on the north side of Vanua Mbalavu; and the following night was passed at anchor in another bay,

beset with limestone islets (Fig. 206) at the northwestern end of the island, a good view of which is given by Cooper in his frontispiece (1880). Boat trips were made around these bays, in the hopes of finding indications of the rock structure; but the limestone, where not covered by vegetation

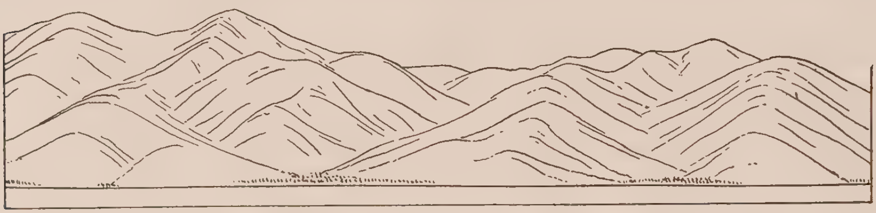


FIG. 204—Volcanic slopes, east coast of Vanua Mbalavu, Exploring Isles, Fiji.

or calcareous incrustation, was uniformly massive; no fossil corals were observed, and bedding planes were rarely seen; where detected they were about horizontal. The limestones were therefore provisionally regarded as lagoon deposits.

Next northeast of Vanua Mbalavu is Avea (Fig. 205), 1½ by 3 miles, 600 feet high, in which maturely eroded volcanic slopes are seen below the retreating cliffs of an unconformable limestone cover; Agassiz was in error in stating that this island is "wholly composed of elevated limestone" (1899, p. 91). Three other islands stand farther east, one of which is Thikombia-i-lau, 1½ miles across and 550 feet high. This island, as well as other members of the group, was critically examined by Foye (1918, p.

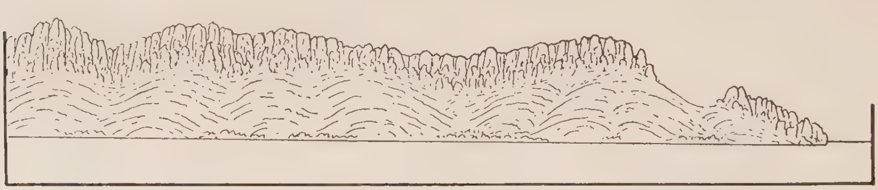


FIG. 205—Rough sketch of limestones on volcanic foundation, Avea, Exploring Isles.

53), who reports that it has a cap of coralliferous limestone resting unconformably on an unevenly eroded surface of volcanic agglomerate and ash.

The large lagoon from which the Exploring Isles rise is peculiar in having greater depths, 60 or 80 fathoms, near the eastern arc of the reef circuit, than on the west, 20 or 30 fathoms, and also in having a channel, the "American Passage," over 100 fathoms deep, leading out from the lagoon through the eastern barrier. Agassiz noted that "these great

depths, far beyond any at which corals can grow, represent the elevated gorges of the slopes of the volcanic peak which probably once extended over the whole area enclosed by the outer reef, during the elevation of which the reef which once covered a part of the same area was lifted to its present or even a greater height" (1899, p. 107); but this seems an impossible interpretation. His suggestion that the eastward increase of lagoon depth is due to a gentle tilting of the region is more acceptable; and to this it may be added that the deep American Passage may represent a valley of erosion in the lagoon floor before the recent downtilting.

FIG. 206—Elevated and dissected limestones, northwest Vanua Mbalavu. (Based on photograph by Stinson, Suva.)

Evolution of the Exploring Isles

The conclusions reached by me regarding the history of the Exploring Isles and their fine barrier reef have been set forth in an earlier paper (1915b, pp. 250–253); they have been confirmed in all essential particulars and extended by Foye (1918) and are in brief as follows: A cluster of volcanic cones, occupying nearly all the area of the present lagoon and of less altitude in the east than in the west, were maturely eroded while standing at a greater altitude than now; for where their eroded surface now lies underneath the limestone cover it appears to descend below present sea level. Part of a single cone is shown, diagram fashion, in sector *A*, Figure 207. Then during a period of subsidence the cluster of dissected cones came to be surrounded by an upgrowing barrier reef, of much earlier origin than the present barrier reef. At the same time fringing reefs sheathed the island slopes and fine-textured lagoon deposits aggraded the intervening space; Andrews records that he here found 300 feet of "beautifully bedded limestone . . . apparently nonfossiliferous" (1900, p. 31) on one of the islands. More than 600 feet of reef and lagoon deposits appear to have been thus accumulated, until only the highest volcanic summits in the west survived as almost-atoll islets, sector *B*.

The compound mass, chiefly composed of lagoon limestones, was thereupon uplifted higher than now, sector *C*, and, while fringing reefs on the flanks of the emerged barrier reef prevented abrasion, the limestones were much eroded, sector *D*, expecially on the eastern or windward and rainy side of their total area; their residuals, perched on vol-

canic foundations, survived chiefly on the western or leeward and drier side. In case any reader hesitates to accept, first, so lavish an accumulation of limestone, and second, so extravagant an erosion of the accumulation, a more economical interpretation may be proposed: After a moderate upgrowth of a single barrier reef around the whole group of original volcanoes, the barrier was drowned by a rapid subsidence and was succeeded by fringing reefs of new generation on the shores of as

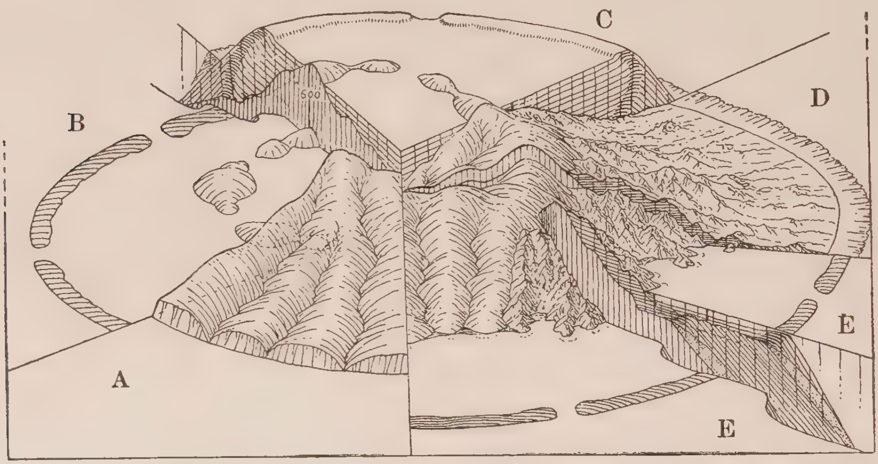


FIG. 207—Sector diagram, illustrating the development of the Exploring Isles and their barrier reefs.

many volcanic islands as were then not wholly submerged: and, as slower subsidence then continued, the new-formed fringes around each island grew up in separate barriers of much smaller total lagoon area than that of the great original barrier.

Whether one large-circuit reef or several small-circuit reefs had been formed at the latest phase of subsidence, the reef and lagoon limestones were greatly eroded during the following epoch of upheaval. The stripped volcanic hills, although somewhat more degraded since their stripping than before they were submerged and covered, preserved the same general form as that of the still-covered hills; this is indicated by comparing the slope of the uncovered volcanic hills with the slope of the contact lines where the limestones overlie the covered volcanic hills. Finally the greatly eroded mass was slightly submerged, for the limestone residuals as well as the volcanic hills are now somewhat embayed, as in sector *E;* and in consequence of this submergence the present large-circuit barrier reef has grown up over the remains of the first-formed large barrier. A part of this submergence is presumably due to the Postglacial rise of ocean level, just as a part of the downwearing before submergence was presumably due to low-erosion during the Glacial epochs. But the fact that the lagoon deepens pronouncedly eastward and has at its eastern side a much greater depth than low-level erosion alone could

produce shows that unequal subsidence as well as ocean rise must have contributed to the recent submergence.

Thus the Exploring Isles have had a three-phase history since their volcanic masses were formed by eruption: a subsidence of considerable measure, accompanied by reef upgrowth and lagoon aggradation; an upheaval of smaller measure, accompanied by limestone dissection and stripping; and a second subsidence of small and unequal measure, accompanied by new reef upgrowth. A vertical section introduced in sector *E*, Figure 207, shows the present relations of the several rock masses, distinction being here made between the residual limestones of the first generation of reef formation and the newer reef and lagoon limestones of the second generation now in process of accumulation. Hence, just as Mangaia with its well preserved, elevated barrier reef gives good evidence of rising, sinking, and rising again, so the Exploring Isles with their much eroded limestone cover give good evidence of sinking, rising, and sinking again. And, like Tuvuthá, the Isles provide good support for the opinion, already reached from an examination of the barrier reefs in western Fiji, that this large and important archipelago occupies an unstable part of the ocean floor, in spite of the fairly accordant depths of its lagoons. The different members of the archipelago as a whole have obviously suffered unlike movements: hence, instead of being described as occupying an area of subsidence alone, as Dana inferred, or of elevation alone, as Agassiz inferred, the Fiji Islands occupy an area that has experienced differential deformation of moderate measure varying in place, date, sign, amount, and rate. Reef formation appears to be closely associated with movements of subsidence, wherever and whenever they have occurred.

Lakemba

Lakemba, 50 miles south of the Exploring Isles, is a volcanic island, 5 by 4 miles, 720 feet high, which bears reef limestones up to a height of 320 feet on its western slope but not so high on the eastern; it is surrounded by a fringing reef from which a barrier-reef loop extends 6 miles to the east. The island has been well studied by Foye (1918, pp. 58–60), who found that, as in the Exploring Isles, the limestones here also rest unconformably on an eroded surface of the underlying volcanic rocks and who therefore inferred that, after the island had been formed by eruption, it was eroded; that it then subsided and was built upon by coral reefs until only some 400 feet of its upper slopes remained above sea level; and that it was next upheaved to its present position. The unconformable contact surface of the reef limestones on the eroded volcanic slope probably extends below sea level; and the island therefore probably stood higher than now during the time of its early erosion. Foye also inferred, from the greater altitude of the reef limestones on the western slope than on the eastern, that the final upheaval had been accompanied by an eastward tilting

which promoted the upward and eastward growth of the present reef loop. But, in view of the great measure of erosion suffered by the uplifted limestones of this belt of islands, this inference may be questioned. Instead of tilting during elevation, a tilting subsidence following elevation and an upgrowth of the barrier-reef loop during this tilting seems more probable. Thus interpreted Lakemba confirms the conclusions as to three-phase history already reached from the study of the Exploring Isles.

Other Members of the Ongea Belt

Next south of Lakemba comes Aiwa, a pair of almost-atoll limestone islets, 2 miles long and 210 feet high, rising from a 20-fathom lagoon encircled by a reef measuring 10 by 2 or 3 miles. This pair of islets is of interest as one of the members of Dana's series of typical reef-encircled Fiji islands selected to represent advancing stages of subsidence; he made no mention of their limestone composition but noted that "the coral ring is singularly large for the little spots of land it encloses" (1849, p. 34).

Oneata, 6 miles southeast of Aiwa, is a narrow, almost-atoll island, probably of limestone, 3 miles long and 160 feet high, rising from a 20-fathom lagoon within a reef measuring 11 by from 2 to 5 miles. Then, 8 miles farther and 3 miles apart, come Mothe, 2 miles across and 590 feet high, and Karoni, less than a mile across and 120 feet high; the first is composed of volcanic rocks, the second of limestone; both are enclosed in a single barrier reef measuring 10 by 2 or 3 miles. Three miles west of Mothe is Komo, a volcanic islet without reported limestone, 2 miles long, 170 feet high, in a 17-fathom lagoon within a 5-mile reef ring.

Eight miles south of Komo is Namuka (Fig. 208), a limestone island 4 by 1½ miles, 260 feet high, surrounded by a barrier-reef lagoon up to a mile wide and 12 fathoms deep. Five miles southeast of Namuka, and 27 miles east of Kambara is the Yangasá cluster of limestone islets (Fig. 208), 390, 210, 240, and 270 feet high, the largest being 2 miles long; all rise from a 19-fathom lagoon enclosed by a reef measuring 8 by 6 miles. These islets are too small to show embayments. Finally, 7 miles beyond the Yangasá reef and only 5 miles east of Fulanga is Ongea (Fig. 208), 4 miles long, 270 feet high, well embayed, with a small companion island on the south, enclosed by a 7-by-5-mile reef; both islands consist of limestone.

Summary for the Ongea Belt

The limestone islands of this eastern or Ongea belt no longer preserve their initial form. But it is believed that they originally had the ring-and-basin form of atolls because there are no known examples of the production of good-sized bodies of coralliferous limestone in Fiji except as atolls and because the less-dissected members of the western or Kambara belt of

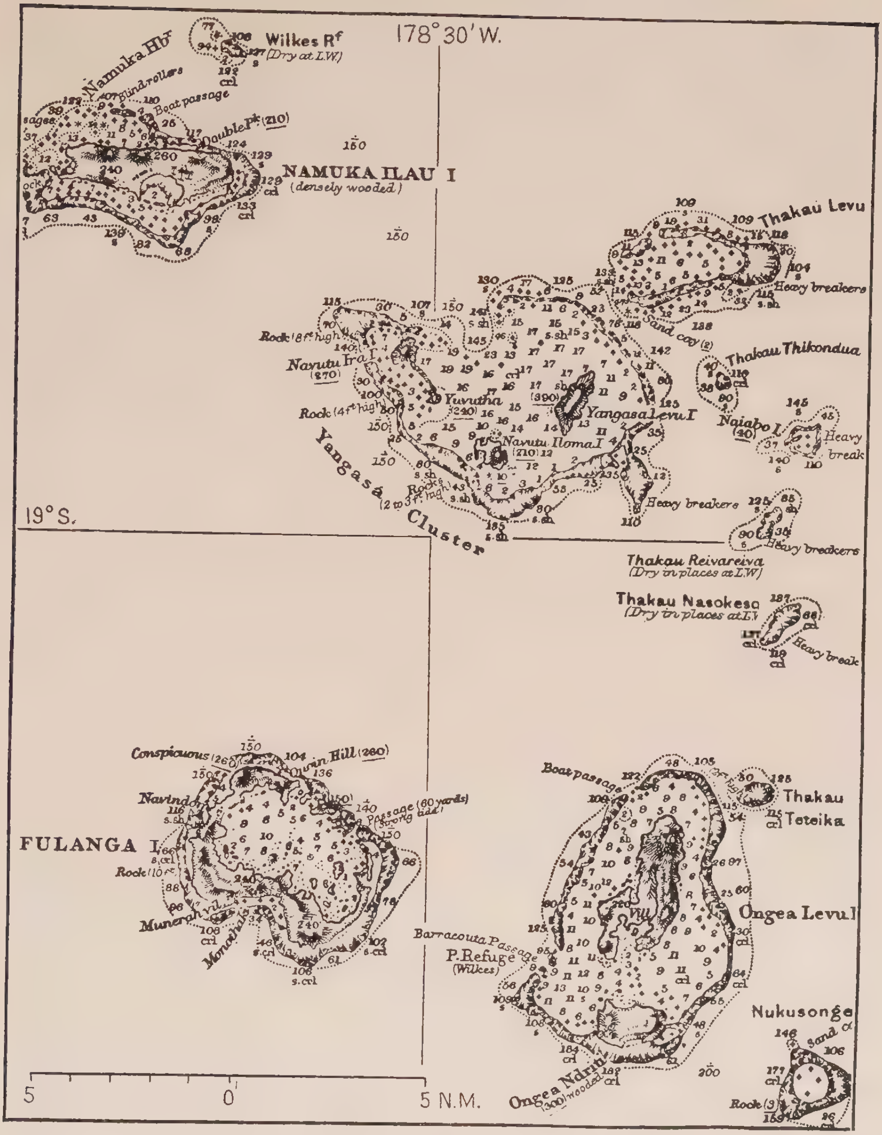


FIG. 208—Namuka, Yangasá, Fulanga, and Ongea, Fiji; HO 2852.

elevated limestone islands still preserve atoll-like forms. Since the dissection of the members of the Ongea belt they appear to have suffered a moderate submergence, due either to island subsidence or ocean rise or both, during which the present sea-level barriers have grown up around them.

In spite of their dissection, most of the islands in the Ongea belt do not show volcanic rocks beneath their limestones. As the height of many of them is still decidedly more than 240 feet, it is manifest that the

foundations of the original atolls, *AA*, Figure 209, of which the present islands, *OOO*, are mere remnants, cannot have been flat, volcanic-rock platforms, *PP*, cut down and built out by low-level abrasion of still-standing volcanoes, *VV*. In other words the original atolls cannot have been formed, before their uplift, in the manner demanded either by Wharton's abrasional theory or by the Glacial-control theory, as has

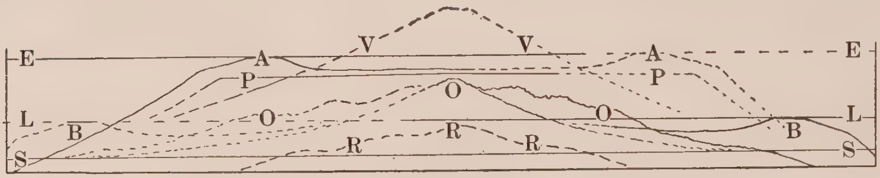


FIG. 209—Evolution of reef-encircled limestone islands; Ongea belt, Fiji.

been intimated in Chapters IV and V and as I have elsewhere shown in more detail (1917).

For if the atolls had been formed according to the latter theory, then one of them, at sea level as in sector *F*, Figure 210, would, after elevation as in sector *G*, exhibit its lagoon plain; and, after much erosion as in sector *H* and more erosion as in sector *J*, the removal of the lagoon limestones would reveal more or less of their volcanic rock platform at a depth of about 250 feet below the original reef crest. Yet, although several islands in the Ongea belt have been more deeply eroded than 250 feet, none of them exhibit any such rock platform as is here figured; although some of them, like Mothe and Komo, exhibit volcanic hills.

Moreover, the residual limestone islands are not cliffed, as they should be, had they been formed and uplifted in Preglacial or early Glacial times and exposed to low-level abrasion in later Glacial epochs. On the other hand, if we interpret the limestone islands, *OOO*, Figure 209, the foundation rocks of which, *RR*, are still hidden, in the way that is demanded by their neighbors in which an unconformable volcanic foundation is visible—and this is surely the most reasonable procedure we can adopt—then all the members of the Ongea belt must have had a three-phase history, like that already inferred for the Exploring Isles: that is, they must have been built up during the subsidence of their eroded volcanic foundations, *RR*, and have reached the atoll stage, *AA*, before the subsidence was reversed into upheaval; they must have then, during and after upheaval, been so deeply dissected with respect to sea level about at *SS*, that their uplifted ring-and-basin forms were lost before the upheaval was reversed into a recent subsidence, by which sea level was relatively placed at *LL*; and during this subsidence, which appears to have been of moderate measure up to the present time, the encircling barrier reefs, *BB*, must have been built up on the eroded flanks, *OO*, of the original atolls, *AA*.

Thus both the original reefs and the present reefs of the Ongea belt

appear to have been formed essentially as Dana and Darwin thought, although neither Dana nor Darwin knew of the changes that the earlier reefs had suffered before the later reefs were formed. It is clear that many inferences enter into this interpretation and carry it far beyond the reach of direct observation; but in that respect the interpretation resembles all other geological conclusions.

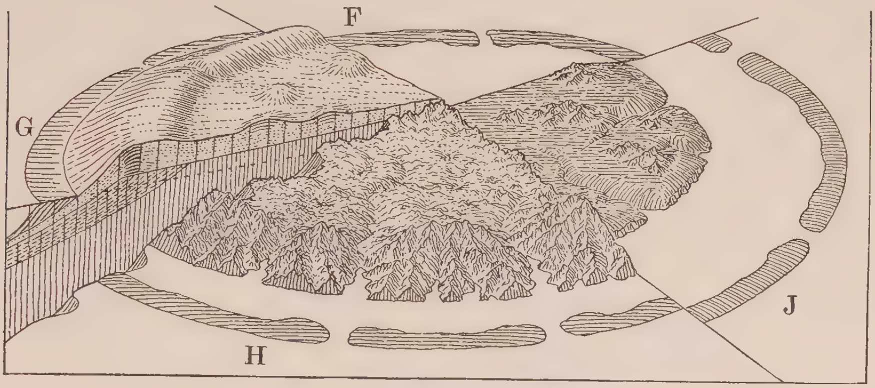


FIG. 210—Sector diagram, illustrating elevation and dissection of an atoll based on an abraded volcanic platform.

Sea-Level Atolls Near Uplifted Atolls

A score or more of small sea-level atolls or almost-atolls stand in close relation with the elevated and dissected islands of the Ongea belt. Those near the Exploring Isles may be specified in preparation for a discussion of their origin. Five miles to the north is Kimbombo, an almost-atoll (Fig. 203), 5 by 3 miles, enclosing 3 excentric islets, one of volcanic rock, 190 feet high, the other two, 120 and 100 feet, of limestone; the lagoon is 12 fathoms deep. Bell, Dibbles, and Williamson reefs are small or minute atolls, 3, 5, and 1 miles in diameter, near by on the east and north. Eight miles northwest of the Exploring Isles is Malima, an almost-atoll (Fig. 201), 3 miles in diameter with 2 central islets 130 feet high and a lagoon 11 fathoms deep; and seven miles farther northwest in Naitamba, an island 3 miles in diameter and 610 feet high, surrounded by a narrow reef enclosing a half-mile lagoon; according to Agassiz this island is partly limestone, partly volcanic; the structural relation of the two rocks is not stated, except that the limestones are briefly said to rest upon volcanic rocks (1899, p. 134).

Now passing to the opposite side of the Exploring Isles barrier reef, the imperfect atoll of Nuku Thikombia, 4 miles long, is found near by on the east; Malevuvu atoll (Fig. 203), 3 miles in diameter, lies 7 miles to the south; and at a distance of 10 miles to the south is an almost-atoll reef, 4 miles in diameter enclosing a lagoon 13 fathoms deep, from which the 1-mile limestone islet of Katafanga rises 130 feet; and a little farther

west is another almost-atoll, 2 miles across, with the minute limestone islet of Vekai rising from the southeast turn of the reef ring. About two miles southeast of Katafanga are three atolls, Tambu, Nokeva, and Lasemarawa 3, 2½, and 4 miles in diameter. A number of other small atolls lie farther south in the Ongea belt.

Evolution of Small, Sea-Level Atolls in Fiji

None of the above-named small atolls is over 10 or 15 miles from the barrier reef of the Exploring Isles; hence they may be assumed to have experienced essentially the same three-phase changes of level as were suffered by those larger Isles and as are represented in the successive sectors of Figure 211. Let attention be first directed to the central part of the sectors, showing the Isles. Sector *A* shows the initial forms due to volcanic eruption; sector *B* shows the forms of well advanced erosion and partial submergence within a well developed barrier reef; sector *C*, the forms of maximum submergence, when only mountain-top islets survive within a well developed almost-atoll reef; sector *D*, the potential form that would result from the uplift of the almost-atoll without erosion; sector *E*, the actually realized forms when, elevation having ceased, the limestone area is for the most part stripped from the volcanic mounts and reduced to low relief; and sector *F*, the forms of today, after the limestone lowland area is submerged beneath the lagoon of a new barrier reef, above which rise the little modified volcanic mounts with their residual limestone patches. (See also Fig. 18.)

Now, returning to sector *A*, let the four small peripheral volcanic cones there drawn suffer the same sequence of changes as those experienced by the Isles. Then these small cones, while suffering erosion and subsidence, become reef-encircled, as in sector *B*, the minute reef over the smallest cone being already extinguished by reason of inslanting upgrowth, as explained in an earlier section. As the subsidence of the Isles continues and produces a large almost-atoll reef in sector *C*, the reefs over the two smallest cones are completely extinguished, while the barrier reefs of the other two cones become little atolls. Elevation of the Isles almost-atoll then takes place; its potential effects are shown also in the two uplifted small atolls of sector *D* and in the resurgence of the reefs on the two smaller cones, one of which rises moderately above sea level while the other just reaches sea level. Degradation of the limestones then follows, as in sector *E*, whereby the eroded volcanic core of the largest peripheral cone is laid bare, with ragged limestone residuals near it and a limestone lowland near them; limestone residuals alone survive in the second cone. Then a moderate subsidence determines reef upgrowth from the margin of the limestone lowlands, sector *F*, and two small almost-atolls, one smaller atoll, and a minute sea-level reef result, closely imitating the features of the small neighbors of the Exploring Isles.

Thus a three-phase history is revealed for these uncommunicative little structures by the more outspoken testimony of the larger structures near them. The lesson of this story is that atolls standing near a more self-revealing structure should be searched for, in order to discover the conditions under which they have been formed. This search will be prosecuted in Chapter XVIII. It is well to point out again, as was done at the opening of Chapter XIII, that the evidence just presented for founda-

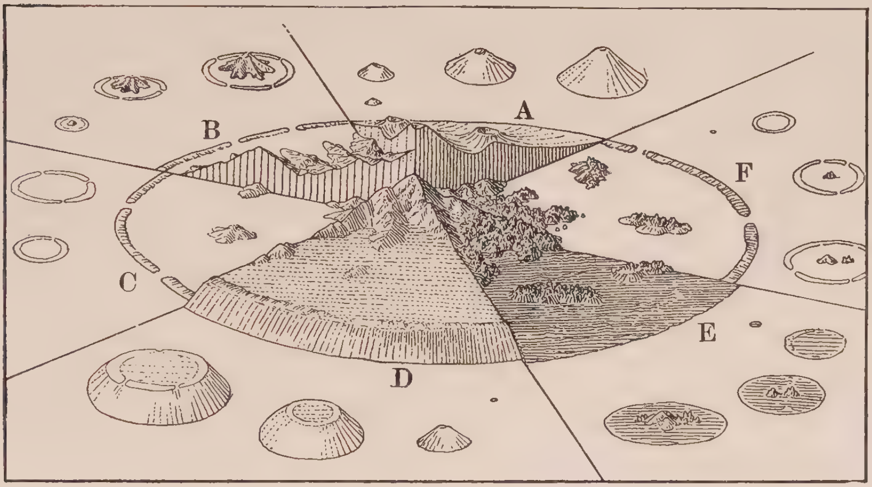


FIG. 211—Sector diagram, illustrating the development of small atolls near the Exploring Isles.

tion subsidence during the formation of the atolls here described is entirely independent of Darwin's postulated depth limit for coral growth, and is therefore confirmatory of the subsidence that that depth limit demands.

It may be pointed out that certain minute sea-level reefs standing near the new-made barrier reefs which encircle the well dissected limestone islands of the Ongea belt here under consideration should not be classed with the minute resurgent sea-level reefs above described in association with the little-dissected limestone islands of the Kambara belt to the west. For here the reduction of the foundation of a minute sea-level reef may have been accomplished in good part by erosion since elevation, instead of only by slanting upgrowth during the preceding subsidence. But it is still possible that extinction by ingrowth during that subsidence, followed by resurgence to moderate height when elevation took place, reduced the task to be accomplished by post-elevation erosion. Similarly, the occurrence of a small sea-level atoll in association with the uplifted and dissected limestone islands of the Ongea belt does not prove that the subsidence during which the limestone islands were formed included a rapid sinking by which the predecessor of the small atoll was drowned. For here also that predecessor may have grown up to a higher level than that of the present small atoll while subsidence

continued, may have been well worn down when elevation took place, and thus worn down may now serve as the foundation for the present atoll reefs since subsidence has again set in. But the occurrence of several medium-sized, sea-level atolls in the Ongea belt, while none such occur in the near-by Kambara belt, is certainly significant.

The Easternmost Atolls of Fiji.

Not many miles to the east and northeast of Lakemba, in the Ongea elevated belt, lie three good-sized sea-level almost-atolls or atolls (Fig. 35). The largest is Argo, 22 by 8 miles across, with a maximum lagoon depth of 36 fathoms; a number of reef patches rise near the lagoon center, as if marking submerged ledges. North Argo is 5 by 10 miles across; its lagoon has a maximum depth of 21 fathoms and contains two minute islets; one of these, half a mile long and 80 feet high, is, according to Agassiz, composed of limestone. Reid atoll is 6 by 8 miles across; from the lagoon rise, again according to Agassiz, three islets, 80, 20, and 10 feet high, probably composed of limestone.

These good-sized atolls and their minute lagoon islets, which will be referred to as constituting the Argo belt, may be interpreted as having had a three-phase history similar to that of the Exploring Isles and other members of the Ongea belt, except that the three phases for the Argo belt are not contemporaneous with but somewhat earlier than the corresponding phases of the Ongea belt. Furthermore, the third phase seems here to be more advanced; for it has already caused the nearly complete disappearance of the dissected limestone islands of the second phase, as well as the development of atolls where only barrier reefs have been developed in the other belt. Evidently, in order for the third phase to be thus so far advanced here, the two preceeding phases must have been dated earlier in the Argo belt than in the Ongea belt, as above stated.

In addition to these atolls several small submarine banks are charted a little farther east in the same region. One is Malan bank, two miles southeast of Reid atoll; it is a mile in diameter and 8 fathoms deep. Others are northeast of the Exploring Isles beyond the above-mentioned little Bell atoll: they are Lookout reef (Fig. 203), a mile across, mostly submerged; the minute Lewis bank under 8 fathoms of water; and about five miles farther northeast the small Jeffries and Alacrity banks, a mile and a half across with depths of 9 and 12 fathoms. If these banks, which will be referred to as constituting the Malan belt, have also had a three-phase history, they are now so far advanced in the third phase as to suffer submergence either by an acceleration of subsidence or by extinction after reduction to small size by inslanting upgrowth. The inferred relation of the sea-level atolls of the Argo belt and the submarine banks of the Malan belt to the Kambara and Ongea belts of elevated islands farther west will be pointed out in a later section.

New Reefs for Old.

The extensive explorations in Fiji conducted by Agassiz led him to the belief that "preceding the present epoch there was an extensive elevation, which lifted the great masses of coralliferous limestone resting upon the flanks of the [Fiji] islands to a considerable height." The limestone masses were said to rest upon "volcanic rocks," but no account was taken of the nature of the contact. "During this period of uplift the physiognomy of the islands of the group must have been greatly changed, and still further modified by the denudation and erosion which have taken place since the elevation of the ancient limestones. . . . It is . . . around the islands and islets which are the remnants of a former period, that the corals of today have obtained a foothold. . . . The submarine platforms upon which the barrier reefs have grown being merely the flats left by the denudation and erosion of the central island, while the atolls are similar flats from the surface of which the islands have at first disappeared and the interior parts of which have next been removed by the incessant scouring of the action of the sea" (1899, pp. 133–134, 135). Subsidence had no place in this theory, because Fiji was believed to occupy an area of elevation.

Many more specific statements, applying to particular reefs, might be quoted. Thus, "the islands which probably once covered the whole area of the Argo Reefs have been disintegrated, and there remain of them only the islets in Vanua Masi [North Argo] and the innumerable heads and patches which stud the slope of the Argo Reefs" (p. 125). In an account of the limestone islets of the Yangaśá cluster, attention is called to a tongue of deep water which runs in from the north toward the center of the lagoon—see Figure 208—and the tongue is explained as probably representing "an original valley formed in the uplifting of the island, and has no connection with a subsidence of the island during the formation of the encircling reef, which has grown subsequently upon the platform of submarine erosion formed by the wearing away of the original land mass" (p. 59). No attention is given to the evidence for subsidence—see Figure 208—presented by the "broad and deep bays, forming small irregularly shaped sounds, which in the case of Ongea Levu have nearly cut that island into two" (p. 61). In connection with these views as to the origin of the present islands repeated reference is made to volcanic forces of upheaval. Thus, regarding the Argo reefs, it is said that their slope "represents the slope of the volcanic island which thrust up the elevated limestones now eroded which once covered the great part of the Argo Reef Lagoon" (p. 125; also p. 51).

Although most of these explanatory views cannot, in my opinion, be accepted for most of the Fiji reefs, there is no question that new barrier reefs and atolls are, somewhat as Agassiz supposed, replacing earlier-formed reefs in the above-described Ongea and Argo belts of uplifted and

dissected limestone islands in eastern Fiji. But, in view of the irregularly embayed shore lines of the larger dissected limestone islands in the Ongea belt, in contrast to the non-embayed shore lines of the non-dissected islands in the Kambara belt near by on the west, and still more in view of the evidence for changes of levels to be summarized in the following sections, it seems wholly unreasonable to exclude subsidence from all share in bringing about this replacement. The exclusion of subsidence is, moreover, all the more unacceptable because it is associated with theoretical views which take no account of unconformable contacts in evidence of subsidence and which ascribe the upheaval of reefs to volcanic forces in areas where volcanic action has long been extinct.

Various Interpretations of Fiji Reefs

The Darwin-Dana View

Before proceeding to an explanation of the facts above detailed regarding the several belts of islands and reefs in eastern Fiji, it is desirable to review the opinions held by various earlier observers as to the origin of the Fiji reefs in general. Darwin had little information about them at the time his theory was set forth; he merely said: "Most of the islands are surrounded by reefs, lying far from the land, outside of which the ocean is very deep" (1842, p. 161): hence the group was tinted light blue on his map, to indicate the occurrence of so much subsidence as is needed for the production of barrier reefs; but in its southeastern corner, where two small atolls had been reported, a patch of dark blue was added. Dana had opportunity, as geologist of the U. S. Exploring Expedition, to visit many parts of Fiji, and he gave account of a good number of reefs in his report; but he made no mention of any elevated reefs or reef limestones in the eastern islands. His conclusion regarding the origin of the sea-level barrier reefs has already been quoted. Regarding the Fiji group as a whole, he wrote: "Its northeast portion consists of immense barriers, with barely a single point of rock remaining of the submerged land; while in the west and southwest there are basaltic islands of great magnitude. . . . A large amount of subsidence is indicated by the reefs in every portion of the group, but it was greatest beyond doubt in the northeast part" (1849, pp. 396, 398). His only mention of elevation concerns the small upheaval of Ovalau and a few of its neighbors, as indicated by their slightly emerged shore lines. It is curious that the elevated atolls of the Kambara belt were not recognized as such by Dana, for their forms appear to be well preserved. When Darwin brought out the second edition of his book on coral reefs, he noted (1874, p. 211) that "full information" concerning Fiji was given in Dana's report, but he quoted no details and made no change in his map. Thus these two leaders who, as young men, made so great contributions to the coral reef problem, treated the whole of Fiji as a region of subsidence.

Dissent from the Darwin-Dana View

At the close of the Darwin-Dana century, Agassiz went to the opposite extreme: "The islands of the whole [Fiji] group have been elevated, and since their elevation have, like the northern part of Queensland, remained nearly stationary, and exposed to a great and prolonged process of denudation and of aerial and submarine erosion, which has reduced them to their present height . . . the windward islands of the Fiji group . . . have been subject to an elevation of at least 800 feet. . . . It is not unnatural to assume that . . . since this epoch of elevation the islands . . . have been, like Northern Australia, subject to an extensive denudation and erosion, many of them being reduced to mere flats but a few feet above the surface of the sea, others worn away to represent today but a small portion of their former extent. It is upon the reef flats thus eroded, or around the islands and islets which are the remnants of a former period, that the corals of today have obtained a foothold" (1899, pp. 133, 135). This interpretation closely approaches that by which Murray also sought to explain the formation of barrier reefs and atolls upon more or less worn-down, still-standing islands.

Agassiz continued: "The outlines of the islands, deeply furrowed by gorges and valleys, the sharp or serrated ridges separating the valleys . . . all attest to the great work of atmospheric agency which must have been going on for so long a period. . . . The platforms of submarine erosion constitute the characteristic features of the islands of Fiji. . . . Add to this the fact that we are in a region of former powerful and extensive volcanic activity, the traces of which can still be seen in all directions, and which has undoubtedly played a great part in the lifting of the island masses and their subsequent shaping to their present outlines. From this evidence I am inclined to think that the corals of today have actually played no part in the shaping of the circular or irregular atolls scattered among the Fiji Islands, that they have had nothing to do in our time with the building up of the substructure of the barrier reefs . . . and that the recent corals living upon the outer margin of the reefs . . . form only a crust of very moderate thickness upon the underlying base. . . . These atolls . . . have not been built (as is claimed by Dana and Darwin) by the subsidence of the islands they enclose. They are not situated in an area of subsidence, but on the contrary in an area of elevation. The theory of Darwin and Dana is therefore not applicable to the Fiji Islands" (1899, pp. 136, 137, 135).

At a somewhat earlier date the Narrative of the *Challenger* expedition did not particularize as to the movements that Fiji has suffered but expressed doubt as to the capacity of Darwin's theory to account for the varied reefs found there: "Throughout the Fiji Islands the three varieties barrier, atoll and fringing reefs are distributed in such a manner as to render it difficult to understand how the two former have been formed [from

the latter] by subsidence" (1885, p. 508). It has already been told that, when the *Challenger* reached the beautifully embayed island of Kandavu in southwestern Fiji, Murray, taking no account of the embayments, gave up Darwin's theory and adopted instead his own theory of reef outgrowth.

It was after hearing of Murray's account of his new theory of reef formation, which had independently repeated the essential features of Semper's much earlier explanation of the Pelew reefs, that Geikie entered the problem. Although he had only the year before said of Darwin's theory that it is "one of the most impressive generalizations with which geology, fertile in such achievements, had yet astonished the world," that its "simplicity and grandeur strikes every reader with astonishment," and that "no more admirable example of scientific method was ever given to the world" (1882), he practically abandoned it. For he then wrote, as if in reference to Fiji: "Upheaval has taken place even in areas where barrier reefs and atolls are in vigorous growth. Such an association of upheaval with an assumed general subsidence requires, on the subsidence theory, a cumbrous and entirely hypothetical series of upward and downward movements" and is therefore to be given up (1883–85, pp. 28, 29).

At a somewhat later time attention was called to the elevated reefs of eastern Fiji and to the uplifted marine deposits of volcanic muds, known as "soapstones," on the south side of Viti Levu in western Fiji by Guppy, who concluded: "We cannot doubt that if these facts had been known to Mr. Darwin, he would never have placed the Fiji Islands in an area of subsidence" (1888, p. 125); and the same painstaking observer, after making an elaborate study of Vanua Levu, in which, however, he gave much more attention to petrography than to physiography, reached the over-simple belief that the history of that reef-encircled island is "one long story of emergence" and that it therefore offered "nothing to support" Darwin's theory (1903, p. 373). Gardiner, who has given excellent accounts of many reefs in the Pacific and Indian oceans, wrote a few years after his study of Fiji: "While it may be true that some reefs really owe their existence to the subsidence of the land round which they originally formed only a fringe, the great mass of facts that has been collected in the past twenty years points out clearly and decidedly that such a method of formation can never have been anything else than rare and altogether exceptional. Elevated reefs, which have been proved to be extremely numerous in coral reef regions, give no evidence of the very considerable thickness which such a view postulates" (1903, p. 204).

If scientific opinions were determined by "authority," the unanimity of the above-quoted opinions as to the incompetence of Darwin's theory to account for the reefs of Fiji would settle the question here in debate; but fortunately there is in science no supreme court clothed with power to stop discussion by pronouncing final decisions. In scientific discussions it is not even necessary for a student of a disputed question to gain per-

mission from a court of appeals to reopen a case which has been declared closed by other students. Dissent is always in order.

A Return to the Darwin-Dana View

In contrast to the foregoing rejections of Darwin's theory, its acceptance for the reefs of Fiji was announced nearly 40 years ago by Moore, who appears to have made hydrographic surveys in that archipelago, and who, after declaring that "the Fiji islands present the most complete collection of coral reefs in the world," wrote: "I believe that it is not inconsistent with the theory put forward by Mr. Darwin that, in the same group, some islands should be rising and some falling at the same time; nor that an island should have fallen to a certain level and then undergone a movement of upheaval. If this be so, there is nothing, as far as one can see, in the Fiji group, which disproves subsidence as the origin of barrier reefs" (1889, pp. 203–204); and he might have added "or of atolls as well." It is a pleasure here to record so fair-minded a theoretical pronouncement by an observer who apparently did not regard himself as a theorizer; for he wrote in close association with the above-quoted passage: "The business of a surveyor abroad is not with theories. It is to collect facts. . . . When he begins to theorize, he may be suspected with some reason of bias, and of insensibly colouring his reports with preconceived notions of what he expected to find, instead of carefully storing up evidence" (1889, p. 203); with this pronouncement I am by no means in sympathy.

The excellent evidence for Darwin's theory presented by Foye, the latest student of Fiji reefs, has already been noted in this chapter, where his accounts of Tuvuthá, Lakemba, and the Exploring Isles are quoted, and also in the earlier chapter on barrier reefs, where the possible occurrence of "platforms" as reef foundations in Fiji was discussed and excluded. One of the passages there cited may be presented again in view of its importance and pertinence in the present review: "As far as observed, the elevated limestones of Fiji rest unconformably on eroded volcanic islands and are believed to have formed atolls and barrier reefs" (1918, p. 10)* It seems to me fair to give greater weight to this conclusion than to the conclusions announced by Gardiner, Guppy, or Agassiz, because it was reached in the knowledge of their opposite views and still more because, in reaching it, application was consciously made of certain essential geologic and physiographic principles neglected by them.

In view of the above summary of earlier opinions, a review may now be made as to the bearing of the facts regarding the islands and reefs of the Fiji group upon the various theories of coral reef origin. Darwin's theory should surely not be overlooked, in spite of the many epitaphs

*Foye, a Harvard graduate student, went to Fiji in 1915 to extend the observations that I had made there in 1914. His geological training was secured largely under Professor R. A. Daly, author of the Glacial-control theory of reef formation, from which Darwin's leading postulate of island subsidence is practically excluded.

that have been written upon it in the earlier essays here cited, as well as in other essays earlier cited in the account of the Great Barrier Reef of Australia; for, as just noted, it is supported by a later and more critical essay, as well as by my own work of intermediate date. In making this review it will be found that the variety of reef forms in Fiji is very great. If contemplated all together and rather hurriedly, they seem to exhibit a disordered confusion; but if examined deliberately, one after the other, their arrangement proves to be orderly enough, although enjoyably diversified. The first conclusion that should be reached regarding them is that, for the eastern part of the group as well as for the western, no explanatory theory is adequate in which subsidence is not an essential factor. The persistence of well-embayed shore lines in the islands encircled by barrier reefs in western Fiji clearly demands the occurrence of subsidence during the upgrowth of those reefs, as has been shown in Chapter XIII. Similarly, the unconformable contacts of the uplifted reef limestones of eastern Fiji on a foundation of subaerially eroded volcanic rocks demands the occurrence of subsidence during the formation of those limestones, in spite of the upheaval that they have later experienced.

The Five Belts of Islands, Reefs, and Banks in Eastern Fiji

The accounts above given of the reefs of eastern Fiji show that a narrow belt of recently uplifted, little-dissected atolls, the Kambara belt of two-phase history, is adjoined on the east by a second belt, the Ongea belt of three-phase history, in which a number of earlier uplifted and much dissected atolls are thought to be recognized, their remnants being now somewhat submerged and encircled by barrier reefs; also, that the second or Ongea belt is followed farther east still by a third, the Argo belt of earlier three-phase history, characterized by sea-level atolls, two of which have minute volcanic and limestone islets in their lagoons. An imperfect fourth or Malan belt includes five banks—Lookout, Lewis, Jeffries, Alacrity, Malan—to the east of the Argo atoll belt. On the other hand, some 50 or 60 miles to the west of the Kambara belt, across a blank space known as the Koro Sea, is the Ngau belt of barrier-reef islands in central Fiji, described in Chapter XIII as beginning with Matuku on the south and ending with Wakaya and Makongai on the north. They have only a one-phase history of reef upgrowth during subsidence.

The changes of level suffered by the islands of these five belts in the past history of the region are now to be inferred. The inferences will be based on the conclusions already reached for Tuvuthá, three of the Exploring Isles, and Lakemba; and the inferences will then be directed to the discovery of the geological changes experienced by the region, without regard to any particular theory of reef origins.

A Westward Migrating Anticline in Eastern Fiji

The islands of the Ongea belt, in which the structure of certain members is well revealed, give a key to the history of all the others. If the subsidence of their third phase is continued, they will in time be converted into atolls. That conversion is already so far accomplished in the Argo belt that only a few minute islets remain in the lagoons of two of the Argo atolls. Hence, as already suggested, the three phases in the history of the Argo belt are of somewhat earlier dates than those of the Ongea belt.

On the other hand, the uplifted but little-dissected atolls in the two-phase Kambara belt may be regarded as having not yet entered upon a third phase of their history. Similarly, the Ngau belt of barrier-reef islands are still in a rather early stage of a first phase. Now, all the varied features of the many islands and reefs in these five belts can be simply reconciled if it may be assumed that a broad and low sea-floor anticline, preceded and followed by sea-floor synclines, has slowly migrated westward into the Fiji region. The breadth of the anticline, measured from the trough of the preceding to the trough of the following syncline, may be some 60 or 80 miles; its height was probably only a few thousand feet. The first generation of atolls, of which only minute residuals now survive in the islets of the Argo-belt lagoons, are thought to have been formed when that belt was reached by the preceding syncline; those atolls were raised and dissected when the anticline advanced upon them; and their dissected remnants were lowered almost to complete submergence and surrounded by upgrowing barrier and atoll reefs of a second generation when the following syncline came along. The banks of the Malan belt may be similarly explained, but the explanation is there supported by so few facts that it need not be insisted upon, even though the few facts presented are consistent with the far-reaching explanation. The uncertainty attaching to the history of this short belt would be diminished if future exploration should discover more and larger and deeper banks somewhat farther east.

The members of the Ongea belt appear now to be on the eastern or back slope of the westward-migrating anticline. Their former ring-and-basin forms of a first generation were best developed when the preceding syncline lowered them in its trough. Their greatest altitude was given when the anticline crest passed them. They will be nearly or quite submerged and their present barrier reefs will become almost-atolls or atolls of a second generation when the following syncline arrives. The high-standing but little-dissected atolls of the first generation in the Kambara belt would appear to have been formed while the preceding syncline was passing them and to have been uplifted as the anticline advanced upon them; they are now upon its broad crest. If this interpretation is correct, a future subsidence awaits them when the anticline passes by and the following syncline comes on. The barrier-reef islands

of the Ngau belt appear to be on the downsinking front of the preceding syncline, not yet reached by its trough: hence they are in the first phase of a possible three-phase history. When the trough of the preceding syncline reaches them, they will be almost-atolls or atolls of a first generation: hence their future form is a long-past form in the Argo belt. When the trough passes them, they will enter on their second phase and experience uplift on the lifting front of the anticline. The changes here

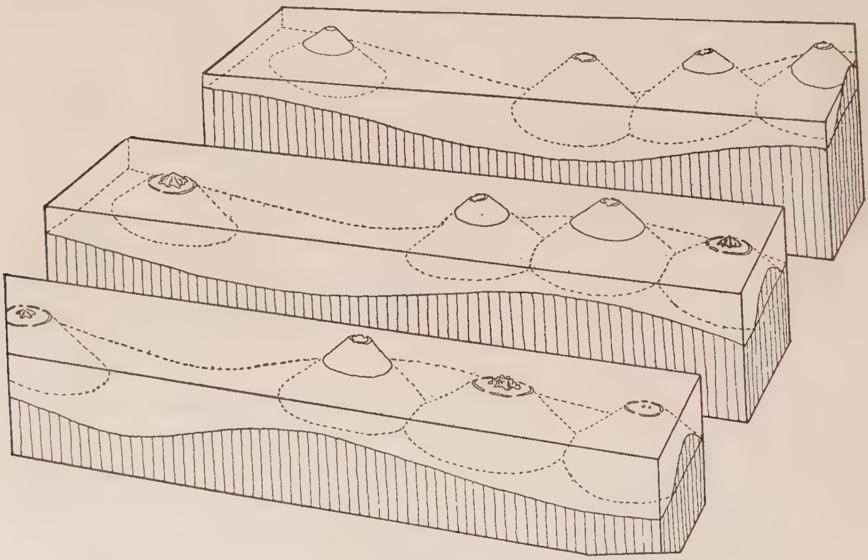


FIG. 212—A migrating anticline in eastern Fiji.

involved may be made clearer by the three-block diagram of Figure 212; in which an early position of the migrating anticline is seen at the right end of the background block, a later position near the right end of the middle block, and the present position farther to the left in the foreground block. Vertical measures are greatly exaggerated. A type island of the Ngau belt is shown at the left end of the background block, where it is a young volcanic cone; as it is lowered by the approach of the preceding syncline it suffers dissection, becomes embayed with diminishing size, and is surrounded by an upgrowing barrier reef in the foreground block. Similarly, a type member of the Kambara belt is seen as an atoll in the preceding syncline of the background block, a partly uplifted atoll with a westward slant of its crest in the middle block, and a completely uplifted atoll in the foreground block. Members of the Ongea and Argo belts are similarly represented more to the right.

Further Consequences of a Westward-Migrating Anticline

It is hardly to be expected that a first reading of the above scheme of a migrating anticline will give a full understanding of it, and even a second

reading may not lead to a conviction of its success in accounting for the facts of the case; but if it be granted a third reading, so that the interaction of its various parts shall be fully appreciated, its competence may be more fully realized. On first reading, it may be regarded as insufficiently grounded. For example, the occurrence of minute volcanic and limestone islets in only two of the second-generation atoll lagoons in the Argo belt may seem to be a slender basis for the interpretation of the whole length of that belt as having sunk, risen, and sunk again. And, truly enough, those islets taken alone would not afford a sufficient basis for applying so broad an interpretation to the rest of the belt. But let the revelations of first-generation almost-atoll and atoll structures given by Lakemba, the Exploring Isles, and Tuvuthá be recalled: it will then be seen that they not only support but indeed demand the interpretation proposed for the Argo belt.

Likewise, the interpretation of the high-standing, little-dissected, first-generation atolls of the Kambara belt as having foundations of subaerially eroded volcanic rocks, although—except perhaps in Yathata—no such rocks are seen there, would be gratuitous if it were based on those high-standing atolls alone; but it is not. The interpretation of these high-standing atolls, the well covered foundations of which have not yet been revealed by dissection, is taken from the neighboring uplifted atoll of Tuvuthá, in which the eroded volcanic foundation is not completely covered by unconformable lagoon deposits, and also from three of the Exploring Isles in which the post-elevational dissection has gone so far as to reveal the eroded volcanic foundation beneath the unconformable limestone cover in a most satisfactory manner. It must be remembered that the small atoll of Tuvuthá and the larger almost-atoll of the Exploring Isles cannot have been selected for exhibition by the processes of elevation and dissection because they alone possessed significant structural unconformities. Those islands, like the elevated barrier reef of Mangaia, must be accepted as impartially chosen samples of their class; and their structural peculiarities should therefore be regarded as holding good for neighboring atolls, whether elevated or at sea level, the foundation of which is hidden.

On still another ground the scheme of the migrating anticline deserves acceptance; namely, on the ground of its capacity of bringing a large number of dissimilar and apparently disorderly facts into simple and systematic relations with each other. It can hardly be a matter of chance that the unlike features of the five sub-parallel belts, Ngau, Kambara, Ongea, Argo, and Malan, should fit as nicely as they do into the scheme of a migrating anticline. To be sure, the anticline and its preceding and following synclines should not be conceived as of rigidly defined forms during their westward migration, and the several island belts should not be conceived as precisely parallel to each other. On the other hand, the marvel is that the anticline is so persistently an anticline

and that the several belts which it defines are so nearly parallel. It would, indeed, be a difficult matter to invent any scheme but that of a migrating anticline which could accommodate all the features of the region so well as that scheme does. Consider, for example, the location of the three banks of the easternmost or Malan belt, just where the syncline following the anticline should cause increasing subsidence. Consider also the way in which Fulanga, standing a little to the east of the line defined by the other members of its belt, partakes of the characteristics of the Exploring Isles belt with which, indeed, it might have been described; for it possesses a well dissected lagoon floor, already partly submerged. Or again, the way in which Tuvuthá, standing somewhat to the east of the little dissected, high-standing atolls in the Naiau belt, partakes of features of the Ongea belt which it approaches, in showing incipient dissection and in being encircled by a well defined although close-set barrier reef instead of by a fringing reef. Once more, note the way in which the large barrier reef of the Exploring Isles takes on the features of an atoll in its island-free eastern part, which extends into the Argo belt. And finally, the way in which the dissected limestone islands of the Ongea belt on the back slope of the passing anticline are embayed, in contrast to the non-embayed islands of the Kambara belt on the crest of the anticline. Something more than accident must lie behind these peculiar correlations.

However, it is always in order to ask for more proof of so speculative a scheme as that of a migrating anticline, which Geikie might have regarded as involving a "cumbrous and entirely hypothetical series of upward and downward movements" and as therefore geologically unacceptable. A fairer judgment would be to regard it, in spite of its manifestly speculative nature, as altogether acceptable geologically, provided it is supported by a sufficient amount of independent evidence. It should be recalled in this connection that Brouwer and other observers have given good reasons for believing in the occurrence of migrating anticlines in the East Indies. The central Alps have recently been affected by a broad, northward-moving anticline, not recognizable in the deformation of its rocks but in the changes of altitude that its surface has experienced. In further confirmation of the Fiji anticlinal scheme, two additional and rather delicate consequences that follow from it will here be noted. They might have been foretold by deduction; but, as a matter of fact, they were unexpectedly come upon by observation. They can be best approached deductively, one at a time, as follows:

When a sea-floor anticline migrates, it will not only cause the islands that it passes to rise and sink but will also cause them to tilt forward as it approaches and backward as it passes by. Such tilting has been well certified in the East Indies. Sea-level reefs need not be expected to exhibit the tilting in so far as it causes submergence, because their growth may counterbalance it; but elevated reefs should exhibit it if they

are not too much eroded, and large lagoon floors may exhibit it if they are not releveled by aggradation. Now it has already been noted that the lagoon floor of the large Exploring Isles barrier reef exhibits a pronounced eastward increase of depth. This fact was not in mind when the scheme of the migrating anticline was invented, but it was soon seen to be an essential consequence of the passing of such an anticline; whereupon the scheme gained the merit of explaining a previously known and rather peculiar fact which it was not invented to explain. The present rate of eastward increase of lagoon depth is not great—probably less than the slant due to the anticlinal flexure; but it is in the right direction, and its measure may have been decreased by aggradation, which tends to change a slope to a level. It may be going too far to add that the deep American Passage in the eastern arc of the Exploring Isles barrier reef seems to record a westward tilting of the lagoon floor, due to the approach of the anticline, before the eastward tilting due to its passing; but no other explanation for that deep passage works so well.

Other indications of gentle eastward tilting should be looked for. They may perhaps be found in the eastern slope of the rim crest of Fulanga, as noted by Agassiz, and also in the inferred eastward tilting of Lakemba and its reef loop, as noted by Foye. It is possible that some of the well dissected limestone islands of the Ongea belt may reveal evenly bedded lagoon limestones in which an eastward inclination is preserved; and such an inclination would be a better record of flexure than the slope of a lagoon floor, where the slant of flexure is reduced by aggradation. (See note, p. 471.)

The Reefless Koro Sea

The second unexpected consequence of the scheme of the migrating anticline may next be stated. It has already been suggested that the absence of sea-level reefs east of the Argo belt may be due to the submergence of any reefs that once existed there by down-sinking in the second or following synclinal trough. The few submarine banks of the Malan belt give some support to this idea. It may now be pointed out that the Koro Sea, 50 or 60 miles wide, may likewise not improbably owe its freedom from sea-level reefs to its occupation by the first or preceding synclinal trough, between the high-standing reefs of the Kambara belt on the crest of the main anticline to the east and the Ngau belt of sinking barrier-reef islands on the front of the preceding syncline to the west.

It is, in any case, rather singular that the only charted reef in the Koro Sea is Navatu or Tova, a small atoll 3 miles across, about midway between Vanua Vatu on the east and Totoya on the west. As it lies at sea level, the axis of the preceding synclinal trough cannot yet have passed it. If there is any truth in this view, future soundings may perhaps discover submerged reefs hereabouts. Inasmuch as there are no moderately emerged atolls next west of the strongly emerged atolls of the

Kambara belt, while the Ongea belt exhibits a number of partly submerged atolls, the front slope of the migrating anticline should be conceived as narrower and steeper than its rear slope.

The Migrating Anticline and Coral Reef Theory

This interpretation for the sea-level and elevated reefs of eastern Fiji has given me much satisfaction, by reason of the ease with which it reduces, as above noted, what at first sight seems to be a region of disorderly complexity to one of orderly simplicity. The changes of level caused by the westward migration of a broad anticline are by no means so elaborate as to deserve the reproach implied in the term "cumbrous"; on the contrary, they are simple and graceful, for they involve nothing more than relatively small and slow elevations and depressions. They are as nothing compared to the gigantic deformations of the Highlands of Scotland, which even Scottish geologists have had to accept in spite of their being truly cumbersome.

Indeed, as compared to those extravagant overthrustings of heavy slabs of earth crust, the little oscillations of eastern Fiji are cannily economical; for they have produced a fine variety of results by a small expenditure of deformation. Furthermore, in contrast to the extreme difficulty with which the intricate Scottish overthrusts were deciphered and the great technical skill and the long-lasting patience demanded for their decipherment—I recall with pleasure witnessing a sample of it during a field day on the Highlands, thirty-odd years ago, in company with the veteran geologists, Peach and Horne—the decipherment of the elevations and depressions of eastern Fiji is like holiday sport. It calls for little more knowledge of earth science than comes with an understanding of such elementary matters as marine deposition, subaerial erosion, unconformable contacts, and embayed shore lines. Guided by these almost self-explanatory principles, the application of which is so well warranted by Tuvuthá and the Exploring Isles, one has little difficulty in passing from the visible facts of the present day to the invisible facts of the past; and, as this passage is made, one is convoyed in safety away from the shoals of earlier misunderstandings and piloted to the safe-harbor anchorage of a well enclosed conclusion.

In view of that conclusion one must give up many earlier views. First, one must abandon the widespread subsidence of all Fiji that Darwin and Dana postulated in order to explain the many sea-level reefs of which they had knowledge, while ignorant of the many elevated reefs of later discovery. Second, one must abandon the equally widespread elevation, coupled with irresponsible erosion and denudation, which Agassiz, overlooking the fact of embayed shore lines and the meaning of unconformable contacts, assumed in order to explain the many elevated reefs as well as the sea-level reefs that he observed. Third, one must reject the outgrowth of reefs around still-standing islands and the solutional excavation of the

lagoons back of the reefs, as imagined by Murray in his ignorance of the abundant physiographic evidence to the contrary. Fourth, one cannot consent to Geikie's rejection of alternating elevations and depressions as objectionably cumbrous. Fifth, one must not share the incredulity felt by Guppy and Gardiner as to the competence of Darwin's theory for the explanation of the Fiji reefs. And, finally, one must exclude the ingeniously contrived abrasional action of the lowered Glacial ocean on still-standing islands as advocated by Daly, for such action is clearly inapplicable by reason of the pronounced instability of the islands under discussion, as well as by reason of the evidence which the non-cliffed islands give that no such abrasional action took place. All these efforts to explain the reefs of Fiji must be left behind as incompetent, and a more competent explanation must be found.

The Success of Darwin's Theory in Fiji

That competent explanation is soon forthcoming. After the facts have been gathered and the recent geological history of eastern Fiji has been worked out, it appears that the formation, the elevation, the dissection, and in some cases the resubmergence of the varied reefs in the several island belts may all be satisfactorily accounted for as commonplace events in that history. The few changes of level demanded, with the associated changes from reef upgrowth during subsidence to reef dissection during and after upheaval, are merely those which a passing, broad and low, sea-floor anticline with its associated synclines will produce. And then, when the persistent association of reef upgrowth with island subsidence is thus discovered, behold, this association is nothing more than a paraphrase of Darwin's old theory of reef formation!

The test with which Darwin's theory is thus confronted in Fiji and which it so successfully withstands, is of a much more serious nature than the one it survives in the Society group. There the islands and their reefs were found to be arranged in an extraordinarily simple and systematic order with respect to the progressive changes called for by the theory; so systematic an order, indeed, that it seems as if the islands and reefs had been so arranged in order to illustrate the theory. Here in Fiji the islands and reefs are distributed in a much more irregular and complicated fashion, as if with the idea of challenging every theory of reef origins to explain them. This they do so searchingly that every theory but one fails to meet the challenge. Darwin's theory alone can account for the facts here displayed; and it does so without any difficulty whatever, as soon as the facts are understood.

That old theory, invented years before the elevated and dissected reefs of eastern Fiji had been discovered, and later condemned and rejected by some of the most experienced students of coral reefs, is today, in spite of all the objections that have been urged against it, in spite of all the obituaries that have been written over it, eminently successful in accounting

for the high-standing as well as for the sea-level reefs in all parts of this wonderful Fiji archipelago, which, as Moore well said, contains the most complete collection of coral reefs in the world. No other theory can for a moment compete with it. The old theory was by many regarded as a failure and was thought, during a period of misunderstanding from 1880 to 1910, to be doomed to extinction; yet it is now as vigorously resurgent as are those reefs which, for a time submerged when a sea-floor syncline was lowering them, are now well above sea level again on the arch of the following anticline. It is not enough to say, as Geikie did, that our astonishment is excited by the simplicity of this wonderful theory. We must add that its irrepressible vitality and its ever-increasing competence compel our unmeasured admiration.

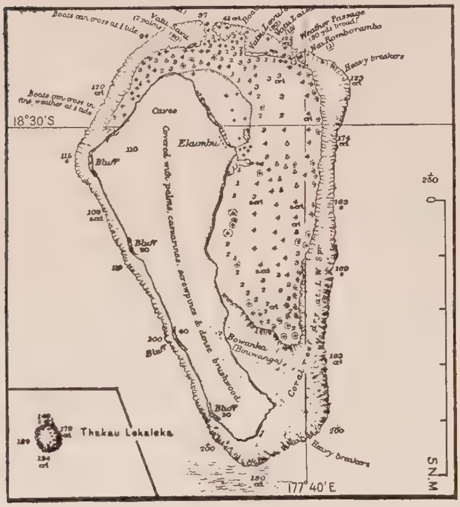


Fig. 213—Vatu Leile, Fiji; HO 2857.

Vatu Leile, a Tilted Atoll in Western Fiji

The foregoing account and interpretation of the elevated reefs in eastern Fiji may be supplemented by a brief description of what appears to be a tilted atoll in western Fiji. Vatu Leile, 25 miles southwest of Viti Levu, HO 2857 (Fig. 213), is 7 miles north-south by 1 or 2 across. It is 110 feet high along its western side, where it falls off in a bold cliff on which, according to Andrews (1900, p. 23, 3 plates), four corniced shore lines are cut at heights of 6, 14, 35, and 45 feet. The island descends by a gradual slope to the east, where it dips into a shallow lagoon, enclosed by a barrier reef. Agassiz ascribed the unsymmetrical form of the island to "denudation and erosion," by which the greater part of an assumed larger original mass is thought to have been removed from the present lagoon area; but he added that the island "must have sloped very rapidly eastward to have attained its present condition" (1899, pp. 68, 70). Moore had previously made the very pertinent suggestion that the island "appears to be raised on one side and depressed on the other" (1889, p. 204), thus dispensing in large measure with erosion in accounting for its present form. This seems to me the better interpretation; for, were the present form of the island due to the advanced erosion of a formerly larger mass, its rather systematic decrease of height from west to east and the small erosion of its corniced shore lines could hardly be explained. Andrews does not mention tilting but notes that at the base

of the eastern slope "long tongues of basalt have been protruded, reaching into the lagoon" (1900, p. 23); but he does not specify the evidence for protrusion.

The Three Loyalty Islands

The Evenly Uplifted Atolls of Mare and Lifu

The three Loyalty Islands are among the finest examples of elevated atolls in the Pacific. They lie northeast of New Caledonia, and it was by unexpectedly good fortune that I was able to visit them on the monthly trip of a trading steamer from that larger island. A day was spent on each one. Mare, HO 2027, 23 by 18 miles, is the southeasternmost of the three. It has a central limestone plain, 150 or 200 feet in altitude, bordered on the eastern or windward side by an even-crested reef rim, from 1000 to 1500 feet wide and rising 100 feet or more above the plain. The outer slope of the reef, which is of simple pattern in plan, is benched at several levels, and a narrow fringing reef follows the shore. The most significant feature of the island is a small hill of dense, soil-covered volcanic rock near the middle of the central plain, to which I was guided by the resident French official.

Grundemann long ago stated that there are many signs of volcanic activity on the island, which he thought was perhaps an ancient crater (1870); but this view gives far too much prominence to its volcanic features. Sarasin, a recent observer, states that the volcanic rock, which he found in two localities, is intrusive into the limestones. My interpretation, based merely on the dense nature of a few boulders of the rock, of which I found no contacts with the limestone, was that it represented the worn-down summit of a long extinct, much eroded, and well submerged volcanic island. Except for its remoteness from a base of supplies, Mare is to be highly recommended as a site for borings around the central volcanic hill; but, if the volcanic rock be truly intrusive, the value of the island as a type atoll would be lessened.

Lifu, HO 2027, 35 by 10 or 20 miles, is of more irregular plan than Mare but resembles it in having a central limestone plain, hardly 100 feet in altitude, and an elevated rim, best developed on the southeast or windward side, which rises to an extraordinarily even crest about double the height of the plain. The exterior slope is benched and cliffed, and a fringing reef follows the shore line. In Sandal Bay, an open bight on the southwest coast, the shore cliffs are well developed and bear several parallel and slightly corniced shore lines (Fig. 214) like those recorded on Aurora near the Paumotus and on Vatu Leile in Fiji. The evenness of the long cliff face was so perfect that I found it difficult, while in its presence, to believe it could be the scar of a landslide and was persuaded that, after a first emergence of the island to a little greater height than now, the cliff had been well cut back by shore waves, that the island was then submerged for the brief cutting of the corniced shore lines at higher

levels in the cliff face, and that it lately emerged again. But the island needs further study.

A low part of the elevated rim of Lifu that I visited near Sandal Bay consisted of massive limestone without a trace of a fossil; it probably represented a trail of reef sand swept by waves and currents from the reef proper. Not far from it, the face of a salient, crowned with a chapel on the western side of Sandal Bay (Fig. 214), was crowded with well pre-

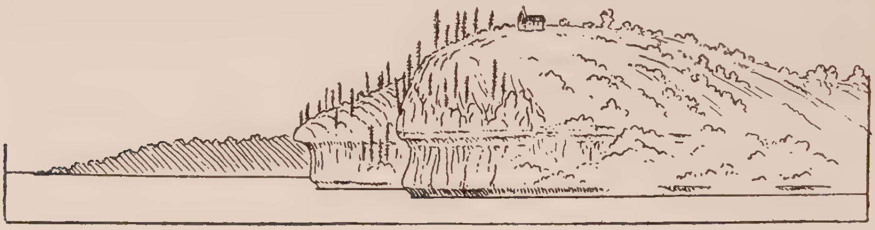


FIG. 214—Corniced shore lines, Sandal Bay, Lifu.

served corals: this must represent an isolated reef patch. Clarke many years ago gave a good description of this island, recognizing it to be an elevated atoll, composed of "dead coral." He wrote: "The general surface of Lafû is that of a table land with such hollows and elevations as now mark the surface of a coral reef. . . . Its present conditions are due to simple elevation" (1847, pp. 62, 63). Garnier recorded that the elevated rim contains much coral and is so rough that it is difficult to traverse (1871, p. 282). Balansa noted that in wells over 100 feet deep in the dry central plain, which represents the lagoon floor, a white limestone of uniform texture is found, occasionally containing a fossil shell but no corals, although corals are abundant on the reef rim of the island (1873, p. 521).

The Tilted Atoll of Uvea

Uvea or Halgan, HO 2230, 25 by from 1 to 3 miles, is a limestone island of rudely crescentic pattern, convex to the east where it is about 200 feet high at the mid-curve, with a gradual and regular decrease of height to its slender, west-pointing horns; Chambeyron, hydrographic expert for New Caledonia, was therefore clearly wrong in describing Uvea as a perfectly horizontal uplift of coral limestone. The curve of the crescent is somewhat angularly completed on the west by a discontinuous loop of small, sea-level reefs. The island therefore seemed to me to be the eastern, emerged part of a tilted atoll; and the loop of reefs seemed to have grown up from the western, submerged part.

It was a surprise to learn that Sarasin, visiting Uvea chiefly for zoölogical investigation, rejected that view and explained the island as the remnant of an atoll evenly uplifted like its neighbors but earlier emerged and greatly worn away by abrasion, the reefs of the western loop being based on the edge of the submarine platform thus produced. Lifu he

regarded as of later emergence and less change; Mare as latest emerged and least changed of the three (1925, p. 135). It does not seem to me possible that the highly specialized form of Uvea can have been produced in this way. If great inroads have been made by ocean waves on its western or leeward side, the horns of the crescent should have been much more blunted than they are; and a fair amount of abrasion should have been accomplished on the eastern or windward face also. Yet a line of soundings of 41 fathoms and no bottom that follows closely around the cliffed shore gives no indication of a shallow wave-cut platform there. Moreover the gentle slant of the astonishingly even reef crest is interrupted by several breaches which closely resemble reef passes and which, by the steepness of their walls, confirm the inference drawn from the evenness of the rim crest that very little erosion has taken place since emergence.

In short, Uvea is so precisely like what an atoll would be if it had recently been gently tilted that the interpretation of this singular island as a tilted atoll is retained. Its chief abnormal feature is Faiaue Bay, a well defined bight on its eastern side, 7 or 8 miles long and 2 or 3 miles reëntrant, which I take to be the result of a landslide prompted by the slanting upheaval and which gives support to the idea that the steep bluffs of Sandal Bay on Lifu, as above described, may be of similar origin.

Thus understood, the tilting of Uvea may be taken to mark the location of a sea-floor flexure where the nearly equal upheaval of the floor under Mare and Lifu slopes away northwestward. If the tilting shown in the emerged reef crescent continues across the lagoon enclosed by the western loop of sea-level reefs, the depth from which those reefs have grown up during the flexure should be 70 or 80 fathoms; yet the lagoon depth, gradually increasing westward, reaches only 18, 20, or 24 fathoms at the most, thus indicating that the floor has been well aggraded. This once more leads to the belief that a subsidence which proceeds at about the rate of reef upgrowth may be fairly well counterbalanced by lagoon-floor aggradation; but it leads also to the unexpected inference, for this case at least, that reef upgrowth from the western, downtilted side of the former atoll has been much faster than reef degradation on the eastern, uptilted side. The long, gently curving shore of the lagoon inside of the reef crescent is composed, for the half-mile stretch along which I followed it, wholly of the comminuted fragments of small, paper-thin, translucent shells, which must thrive exceedingly on the lagoon floor.

About ten miles northwest of Uvea is Eo or Beautemps-Beaupré atoll, with a narrow but fairly continuous sea-level reef rim, 7 miles in diameter. Although this reef must have been in all probability depressed in some degree by the downtilting of the sea floor to the west of Uvea, it has succeeded in maintaining its crest at sea level; and the single sounding charted in its lagoon is only 12 fathoms. Between Lifu and Mare are several much smaller and lower emerged reef islands, which must have

been extinguished when their larger neighbors lay at sea level and which are now resurgent in consequence of the sea-floor upheaval.

Suess on the Emergence of the Loyalty Islands

The three Loyalty Islands may be taken as good exemplifications of the view held by Suess, that high-standing limestone islands in the Pacific all have about the same altitude of 100 meters, more or less, and that they record the former level of the ocean, from which the present level has departed by a universal or eustatic subsidence (Vol. 2, 1888, pp. 399–402). But, as a matter of fact, not only the altitudes of various emerged limestone islands but also the amount of the post-emergence erosion suffered by them varies greatly.

Eua, in southern Tonga, the highest in the open Pacific, has a summit altitude of 1078 feet; its upper limestones are more or less eroded, but they are not wholly stripped off of the underlying volcanic mass. Vatu Vará, in eastern Fiji, comes next with a height of 1030 feet; Andrews records, as already noted, the occurrence of several corniced shore lines on its slopes, thus proving a very small post-emergence erosion. The rim-and-basin members of the Kambara belt of islands in Fiji stand at various lesser altitudes and are also little eroded; but the members of the adjacent Ongea belt are so much eroded that they have lost their initial forms and are reduced to irregular residuals. Hence, instead of a universal and synchronous and uniform emergence of all these islands, we must imagine local emergences at different dates and by different amounts.

Others besides Suess have regarded the emerged Loyalty Islands as standing still and the ocean as sinking. Thus Blin proposed that their emergence resulted from a change in the earth's center of gravity, which caused a lowering of the Pacific: "Les profiles des Loyalty, terminés en forme de marches horizontales, accusent clairement que Maré doit son altitude à quatre baisses de l'océan, Lifu à trois, et Uvéa à deux" (1881, p. 32). Bernard, who had concluded that Darwin's theory of upgrowing reefs on subsiding foundations was too hasty a generalization and felt obliged to give it up, was nevertheless willing to follow Suess in his ill-founded generalization as to the emergence of the Loyalties, in spite of there being no signs of similar emergence on New Caledonia and many other islands.

Age of the Loyalty Limestones

One of Sarasin's results is that the fossil fauna of the Loyalties, as determined for him by Tobler, is of Miocene date; and we thus have here a quandary like that encountered on Mangaia in the Cook group. For if the Loyalty reefs, after having been built up to sea level in Miocene time, postponed their elevation until the recent date indicated by the small amount of erosion suffered by them, then the inner side of the reefs ought to slope down very gradually to extremely shallow lagoons; but,

as a matter of fact, the reefs have steep slopes on their inner as well as on their outer sides, and their lagoons before emergence were 15 or 20 fathoms deep. On the other hand, if the islands were upheaved shortly after their reefs were steeply built up to sea level in Miocene time they ought now to be greatly eroded; and they are not. The best escape from this quandary seems again to be, from a physiographic point of view, the conclusion that the fossil forms which are elsewhere limited to the Miocene survived to later dates in the western Pacific.

Elevated Atolls in the New Guinea Region

Elevated Atolls in the Solomon Group

Guppy's volume on the Solomon group includes an account of a few small islands, largely composed of bedded volcanic tuffs, on which high-standing reefs occur in such forms as to suggest that they were almost-atolls or atolls before elevation (1887, pp. 86, 93, 106, 115); but, as the apparently unconformable contact between the reef limestones and the beds of tuff on which they lie was not recognized, it was very naturally thought that the reefs had been formed during pauses in the upheaval of their foundation. Several examples may be described in some detail.

Treasury Island, in the northwestern part of the group, 5 by 9 miles across, 1150 feet high, has a nucleus of volcanic rock overlain with bedded tuffs, which contain marine fossils and are "covered by a crust of coral limestone," from 70 to 100 feet thick at lower levels but less thick above, where the limestone appears to have been much eroded. Guppy's diagrammatic section of the island shows the tuff beds in undulations, which might be taken to represent irregular deposition on an uneven foundation, were it not that the beds have rising outcrops on some of the exterior slopes. Ugi Island, 6 by 2 miles, 500 feet high, is of similar structure, except that it shows no nucleus of volcanic rock. Here some of the folds or "curves into which the beds have been thrown" have dips of 35° or 40°. The limestone cover on this island is therefore manifestly unconformable on the tilted tuff beds; the same relation probably obtains on Treasury also. Santa Anna, an "upraised atoll" in the extreme southeast of the group, is nearly circular and 2 miles in diameter; its level rim, from a quarter to a third of a mile in width, is 100 feet high on the south and southwest but rises elsewhere to 200 feet; on the east side it is surmounted by a small hill, 470 feet high, composed of gabbro covered with coral limestone. The rim encloses a basin in which lie two small excentric lakes among low knobs of volcanic rock.

All these islands seem to represent moderately elevated atolls, the limestones of which were formed during the subsidence of their deformed and subaerially eroded foundations, in spite of the submarine origin of the foundation strata in the two first named. The islands must therefore have suffered two upheavals and an intervening subsidence. The origin

of the atolls by upgrowth during subsidence is further suggested by what has been told in an earlier chapter concerning the unconformable fringing reefs of the Solomon Islands, which so clearly demonstrate the subsidence of some of the islands before their recent elevation.

Elevated Atolls Near the Solomon Group

Bellona and Rennell Islands are elevated atolls lying about 100 miles south of the Solomon group. The first is 20 miles in circumference; the second measures 50 by 7 or 8 miles. According to Woodford, Rennell "seems to be an old reef with an enclosed lagoon which has been bodily and regularly upheaved to a height above the sea of about 300 feet"; it has a red soil and is forest-covered; when viewed from a distance it "presents the appearance of a long flat island, perfectly level in outline, fringed with perpendicular cliffs of rugged coral" (1916, p. 45). The same island is described by Deck as composed of coral limestone, measuring 45 by 15 miles, with steep walls 300 feet high descending to deep water near the shore; he states also that the interior depression contains a saline lake, 10 miles long, which he takes to represent the "crater of a volcanic peak round which the island has been formed" (1921, p. 475). As no volcanic rock is reported from the island, this explanation seems to be traditional. Nissan or Sir Charles Hardy island, between the Solomon group and the Bismarck Archipelago on the northwest, is described by Schmiele (1891) as a raised atoll 15 miles in diameter; its elevated rim, 2 or 3 miles wide and interrupted by 3 passes on the northwest, encloses a shallow lagoon. As the reef rises to heights of from 130 to 200 feet on the east and only to 65 or 80 feet on the west, a gentle tilting may have accompanied the elevation. Before elevation the lagoons of both these atolls must have been of ordinary depth. Abgarris atoll, HO 2943, 17 by 5 miles, and a companion atoll, 7 by 5 miles, lie 70 miles northeast of Nissan.

Elevated Atolls North of New Guinea

North of Misima, in the Louisiade Archipelago, and 80 miles distant from it, lies Woodlark or Murua Island, HO 2942, 35 by 7 miles, 1345 feet high, with limestone cliffs along part of the shore, suggesting the occurrence of elevated reefs. Farther north still is Kiriwina or Trobriand Island, which appears to be an inclined and incompletely emerged atoll of irregular outline: it begins as a narrow, sea-level reef, trending north for 20 miles; it then rises for a distance of 25 miles and gains a width of from 1 to 6 miles and a height of 100 feet; from its northern end a series of ill-defined reefs extend southwestward. A number of well-defined raised atolls of small size occur in this region, all on HO 2942. Kitava, 2 by 3 miles, has a rim 400 feet high, enclosing a basin floor 100 feet lower; Gawa, 2 miles in diameter, is of the same height as Kitava; Kwaiawata,

1 mile diameter, with a rim 500 feet high, has a basin floor 325 feet above sea level; Dugumenu is half a mile diameter and 220 feet high; Iwa, 1 mile in diameter and 400 feet high, shows "a series of irregular coral terraces and precipices"; its cliffs are ascended on ladders. The lagoons of these atolls, so far as the records go, appear to have been of ordinary depth.

The Schouten Islands, which front Geelwink Bay on the north coast of western or Dutch New Guinea, are described by Feuilletau de Bruyn (1921) as consisting of deformed sandstones and marls with a more or less complete cover of coral limestones. The largest island, Biak, 43 by 23 miles, is about half covered with limestone, mostly at altitudes of a few hundred feet; but in the north the limestones rise to an altitude of nearly 2000 feet with a profile like that of a volcano. The island must therefore have been represented by a small atoll when it was most depressed and the highest limestones were formed; and, as the limestones would seem to lie unconformably on the deformed and therefore probably eroded sandstones and marls, the formation of the atoll must have been associated with subsidence.

The small Padiado Islands, next to the east, also appear to have originated as atolls as they now, according to the same observer, consist of coralliferous limestone at heights of 200 or 300 feet. They are at present suffering active abrasion, by which some of them appear to have been converted into shallow banks. If these banks later become reef-encircled without change of level, the resulting atolls would exemplify Agassiz' theory of atoll formation. These many elevated atolls in the Solomon and New Guinea region cannot be regarded as having been formed on stable foundations; yet in several cases their lagoon-floor plains seem to lie at moderate depths below their reef rims.

Elevated Atolls in the Dutch East Indies

Goram and Other Islands

Several accounts of limestone islands that appear to be elevated atolls are given by Wallace in his famous book on the Malay Archipelago. The most detailed description concerns the small island of Goram or Gorong, 35 miles southeast of Ceram, HO 3003, 4 by 8 miles, 1017 feet high, regarding which it is said: "The land rises gradually to a moderate height, and numerous small streams descend on all sides. The mere existence of these streams would prove that the island was not entirely coralline, as in that case all the water would sink through the porous rock . . . but we have more positive proof in the pebbles and stones of their beds, which exhibit a variety of stratified crystalline rocks. About a hundred yards from the beach rises a wall of coral rock ten or twenty feet high, above which is an undulating surface of rugged coral which slopes downward toward the interior, and then after a slight ascent is

bordered by a second wall of coral. Similar walls occur higher up, and coral is found on the highest point of the island. . . . If the island were again elevated about a hundred feet, what is now the reef and the shallow sea within it would form a wall of coral rock and an undulating coralline plain exactly similar to those that still exist at various altitudes up to the summit of the island." Elevation has taken place "at a comparatively recent epoch, for the surface of the coral has scarcely suffered from the action of the weather, and hundreds of sea shells, exactly resembling those still found on the beach, and many of them retaining their gloss and even their color, are scattered over the surface of the island to near its summit" (1869, pp. 375, 376).

Not less interesting than this admirable description is the hearty acceptance given to Darwin's theory for the explanation of the reefs, and therewith the interpretation that the successive reef walls were formed not during pauses in the recent elevation of the island, as is so commonly assumed in similar cases by other observers, but during pauses in an earlier subsidence: "This peculiar structure teaches us that before the coral was formed land existed in this spot; that this land sunk gradually beneath the waters, but with intervals of rest, during which encircling reefs were formed around it at different elevations; that it then rose to above its present elevation, and is now again sinking. We infer this, because encircling reefs are a proof of subsidence" (1869, p. 376). Although the word "unconformity" is not used by Wallace, he appears to have recognized the structural relation that the word names and to have correctly interpreted the physiographic history that it implies.

Wallace described several other raised atolls more briefly. Manowolko, 5 miles southwest of Goram, 11 by 3 miles, 1116 feet high, "is a mere upraised coral reef. Two or three hundred yards inland rise cliffs of coral rock, in many parts perpendicular, and one or two hundred feet high. . . . There is no other kind of rock and no stream of water. A few cracks and chasms furnish paths to the top of these cliffs, where there is an open undulating country" (p. 370). The smaller Matabello or Watu-bela islands, 15 miles farther southeast, are "formed of raised coral rock. . . . The villages are situated on high and rugged coral peaks, accessible only by steep, narrow paths, with ladders and bridges over the yawning chasms. . . . Every drop of water has to be brought up from the beach," where the ground water of the island evidently comes forth (pp. 371, 373). Weber describes Glisser, in the same region, as a flat coral island with a shallow lagoon (1902, p. 79); it is apparently a slightly emerged atoll.

West of the westernmost peninsular end of New Guinea and north of the good-sized island of Misool, is the smaller island of Kofian, 18 by 6 miles, which Weber (1902, p. 71) describes as showing an even profile of small height surmounted by several hills, the highest of which rises 853 feet. Farther north, near the district of the drowned barrier reef between

the large islands of Batanta and Waigeo, mentioned in the following chapter, are the Jef Fam Islands, also shown by Weber (p. 70) to have an even profile slanting gently to the west, surmounted by small hills. These islands appear to be elevated almost-atolls; but much more exploration is needed before the lessons of so disturbed a region can be fully learned.

The *Challenger* visited this region and recorded that "Kanalur Island, the southern island of the Nusa Tello group, is of considerable size, and rises in a succession of terraces to a height of 1600 feet. . . . All these islands appear to be of coral formation. Even Kanalur . . . looked like a succession of raised reefs" (1885, p. 558). Brouwer, a more recent observer, briefly describes Teor or Tiur, 10 miles south of Matabello, as composed of serpentine conglomerate covered with reef limestones; also the small islands known as the Three Brothers, 45 miles south-southeast of Teor and 96, 162, and 492 feet high, as consisting of gneiss and schist bearing reef terraces, the highest of which makes the flat top of the island (1918). These reef limestones must evidently rest unconformably on an eroded surface of their crystalline-rock foundation, and the atoll reefs which finally crowned the islands must have grown up during a subsidence of their foundation.

Salayer, south of Celebes, HO 3046, 50 miles long, north-south, by 10 miles wide, 1020 feet high, is described by Weber (1902, p. 88) as composed mostly of coral limestones, with gentle slopes to the west and a steep descent to the east, where volcanic foundation rocks are visible; this island would therefore appear to be a tilted atoll. Next to the south are three small islands, HO 3006, from 236 to 745 feet high, adjoined on the west by a 10-mile bank, 17 to 23 fathoms deep, with an imperfect rim; tilting seems probable here also.

The Tukang Besi Islands

The most significant group of elevated atolls in the Dutch East Indies includes those associated with the several sea-level atolls of the Tukang Besi Islands in the Banda Sea southeast of Celebes, Dutch chart 317. The islands are arranged in four sub-parallel belts, 35 to 50 miles long northwest-southeast and 10 or 20 miles apart, or 50 miles over all, southwest-northeast. The first and third belts include only sea-level atolls; the second and fourth, only elevated atolls. They have been well and appreciatively described by Escher (1920). The following details concerning the reefs and islands are taken from the Dutch chart.

The first synclinal or atoll belt includes Karang Kapotta, 10 by 3 miles, with a reef flat from half a mile to a mile and a half across and a lagoon from 18 to 25 fathoms deep; and Karang Kaledupa, 27 by from 4 to 7 miles, with a reef flat 1 or 2 miles wide and a lagoon from 15 to 23 fathoms deep. The second synclinal or atoll belt includes Ndaa, a mile across; Koro Maha, 3 miles across with lagoon depths of 10 to 19 fathoms; and

Koka, 5 miles across with lagoon depths of 17 to 24 fathoms. The first anticlinal or high-island belt includes Wangi-Wangi, 10 by 7 miles, 900 feet high, with narrow fringing reefs around its shore, and two smaller, fringing reef islands near by; Kaledupa, 10 by 2 miles, 660 feet high, with a fringing reef on the southwest side and a barrier reef 2 miles off the northeast side; Tomea, 7 by 3 miles, 880 feet high, with a narrow fringing reef; Lintea, 1 by 2 miles, 270 feet high, with a barrier reef enclosing a lagoon 7 by 4 miles across and 13 or 14 fathoms deep; and Binonka, 10 by 4 miles, 730 feet high, with a fringing reef. The second anticlinal belt has only a single island, Runduma, 1 by 2 miles, 250 feet high, with a fringing reef. All the anticlinal islands bear elevated reef crowns.

The normal depths in the lagoons of the sea-level atolls, which are now in the making, is good confirmation of the ability of aggradational processes not to lag far behind reef upgrowth in building up lagoon floors. As the observed lagoon depths here accord very well with the depths of similar-sized atoll lagoons in the open Pacific, it may well be that some other factor than long-maintained stability of reef foundations controls the depth of Pacific atoll lagoons. Weber records that Binonka "se présente comme un récif de coraux soulevé, sur lequel se montrent nettement les diverses terrasses horizontales de la formation primitive du récif; toutefois ces terrasses tombent à pic. Cette déclivité était si abrupte que les habitants du kampang Popaliha même devaient se servir d'échelles pour descendre à la mer" (1902, pp. 97, 98).

The Lofty Almost-Atolls and Atolls of Timor

In addition to the unconformable reef terraces of moderate thickness on the north and south slopes of the long island of Timor, as mentioned in the preceding chapter, heavier unconformable reefs are found near the island crest; they must have been formed when this land was so greatly submerged that only a few of the highest summits remained above water. According to a personal letter from H. A. Brouwer, the axis of the island was then represented by a shallow sea beset with coral reefs around occasional outstanding peaks. The highest reefs, some of which have a considerable thickness, are believed to have been formed during the approach of the subsidence climax; some appear to have been atolls, others were almost-atolls. Since then they have been greatly elevated, for their maximum altitude at present is nearly 4300 feet; they are therefore the loftiest elevated reefs known. They are now much eroded, the best preserved parts being on the divides between the streams.

The Kei and Aru Islands

The Kei Islands, HO 3026, include one long, narrow member, 47 by 1 to 5 miles, 2628 feet high, and another 22 by 7 miles; both have embayed shore lines and many little satellites. They consist mostly of deformed rocks but have a partial cover of raised coral reefs. Wallace said of these

islands that the limestones are "everywhere broken into jutting peaks and pinnacles, weather-worn into sharp points and honey-combed surfaces" (1869, pp. 419, 428). They have no running streams, but springs issue on the beaches.

General accounts of the islands, which do not, however, add much to our knowledge of their physiographic development, have been prepared by Veth (1877), Langen (1888), Hoëvell (1890), Martin (1890), and Wertheim (1892). Brouwer later states that, while many of the Kei Islands consist wholly of reef limestones, exposures of mica schist and other ancient rocks are also found (1916, pp. 45, 49); the limestone contacts with such rocks must of course be unconformable, and the reefs that they represent must have been formed in association with subsidence. Gregory, the latest writer about this group, states that there are 40 smaller islands, all under 400 feet in height; some of these show a core of older rocks, but most of them consist only of raised coral limestones (1923, p. 24; also 1924): the small islands must therefore have been atolls before they were elevated, unless they represent the detached portions of a barrier reef that encircled the larger islands.

Farther east are the Aru Islands, HO 3027, including four large, reef-fringed members, separated by narrow but well defined channels, and many small islands, 95 by 20 miles over all. This group has already been mentioned as rising from the great Sahul Bank that unites New Guinea and Australia. Earle long ago gave an account of the islands (1845, p. 363). Wallace described them as composed at least in part of coralliferous limestones with marginal cliffs. Little information concerning the origin of the islands is given by later authors, some of whom seem to retain belief in a violent geological philosophy, as they suggest that the separation of the islands by their channels is due to the shattering of a formerly united island when it was uplifted.

The Small Island of Roti

The small island of Roti, next west of Timor, is shown to be of special interest by Brouwer's account of it (1914, supplemented by a personal letter). The island consists of strongly deformed and eroded strata, unconformably terraced with reef limestones. The highest terrace, at an altitude of 700 feet, represents a former atoll. But, singularly enough, the atoll limestone is separated from its foundation of much older rocks by layers of deep-water Globigerina limestone. Hence, while the lower reef terraces must be regarded as fringes or barrier reefs, some of which were presumably formed during pauses in the subsidence of the island, the occurrence of the deep-water limestone over the top of the older rocks proves that the final subsidence was too rapid for reef upgrowth and that the island-crowning atoll is of later origin. It must therefore have been formed, as Brouwer points out, during a pause in the upheaval by which the for-a-time deeply drowned island has been brought above sea level

again. As the eroded surface of the deformed older rocks appears to descend below present sea level, the recent upheaval would seem to be less than the earlier subsidence.

The nearest parallel to Roti is found in Barbados, the easternmost member of the Lesser Antilles; on that island, as Harrison and Jukes-Browne have well shown (1890), a series of fringing-reef terraces overlie a mass of deformed and much eroded clastic strata; but, as a thin deposit of oceanic limestone lies between the island mass and the reef terraces, one must suppose that after the strata of the island—probably part of a formerly more extended continental shelf of South America—were upheaved, deformed, and eroded, the resulting island was rapidly submerged; that while it was submerged it received a thin cover of oceanic deposits; and that while it was intermittently rising to its present altitude, fringing reefs were formed around its temporary shore lines. The atoll crown of Christmas Island in the Indian Ocean will shortly be shown probably to belong in the same class with Roti and Barbados. These three islands therefore exemplify, after a fashion, the Rein-Murray theory of oceanic banks, upbuilt by pelagic deposits, as atoll foundations. But all three of the exceptional cases were submerged by subsidence before they were upbuilt, the measure of their pelagic upbuilding was small, and the opportunity for atoll reef growth was finally given more by upheaval than by upbuilding. Hence the exemplification is very imperfect; but, all the same, these islands give the best exemplification for that theory yet discovered.

North of Bali and Lombok, not far from the margin of the great Sunda Bank, is the island of Kangean, 21 by from 3 to 12 miles, believed to consist of uplifted coral limestone. It is adjoined on the east by many smaller islands, thus constituting a group measuring 47 by from 7 to 15 miles over all. The larger island is for the most part a plain of moderate height; but it includes a summit 1197 feet in altitude and is therefore thought to represent an unevenly uplifted almost-atoll. Karang-takat and the Raas Islands, 10 and 30 miles west-southwest of Kangean, appear to be slightly emerged reefs of small size.

Elevated Atolls in the Indian Ocean

Christmas Island

Christmas Island, 200 miles south of western Java—not to be mistaken for the broad-reefed Christmas Atoll in the mid-Pacific—HO 1170, is 12 by 9 miles across and 1195 feet high. It is an elevated, limestone-covered island with benched slopes; its upper levels have been worked for phosphates. Accounts of the island have been published by Lister (1887), Wharton (1888), and in more detail by C. W. Andrews (1899, 1900). Its exploration has evidently been difficult by reason of a jungle cover. According to the last-named observer the summit of the island is a

plateau with a slightly raised rim; he therefore regarded it as a shallow lagoon floor surrounded by an atoll reef. The limestones of this high-level reef, hundreds of feet in thickness, rest upon Eocene marine limestones, which may be in turn presumed to rest upon volcanic rocks, exposures of which are found at lower levels; but it is not clear whether the volcanic rocks found there may not be intrusive. However, if they represent an eroded island of earlier origin than the limestones, which would in that case lie unconformably upon them, then this island might be, as above suggested, a third example of the Roti and Barbados class. The island slopes bear wave-cut cliffs and fringing reefs at various levels, which are taken to have been abraded and built during pauses in the upheaval by which the atoll crown was given its present great altitude.

Andrews stated in his monograph: "We do not find the great thickness of reef limestones required by the Darwinian theory of atoll formation, and although there may be some evidence that subsidence did occur in the early history of the island, it is clear that it was neither continuous for any long period nor of any great extent" (1900, p. 269); also: "It seems very probable that it is the general level of the surface of the sea that has been altered in giving the island its present altitude, and not merely a local upheaval of a limited land area that has taken place" (p. 298). The first statement shows a misapprehension of Darwin's theory, which demands a strong subsidence only where high islands have been deeply submerged and built up with heavy reefs. The second statement, like the similar statement made by Suess concerning the Loyalty Islands, is unconvincing because it does not include any inquiry as to the associated occurrence of equivalent and contemporaneous emergences elsewhere and because it takes no account of the extravagance of the process of island emergence which it adopts. If the emergence of Christmas Island by 1200 feet is due to a lowering of the ocean surface, then either the whole ocean bottom must have been lowered by that amount, and this would involve an equivalent emergence of all other islands and of all continental coasts as well unless they were lowered also; or a part of the ocean floor must have been lowered by as many times 1200 feet as it is smaller than the whole. On the other hand, the emergence of Christmas Island by 1200 feet in consequence of a relatively local upheaval of the ocean floor by that amount beneath it is strictly economical. Inasmuch as other Indian Ocean atolls, next to be considered, are little emerged, while scores of Pacific reefs are not emerged at all, local movements of upheaval should be regarded as a much more probable cause for the emergence of raised reefs than a eustatic lowering of the entire ocean.

Other Raised Atolls in the Indian Ocean

Agalega, 400 miles northeast of Madagascar, seems to be a slightly raised atoll of figure-8 shape, 12 miles in length. Aldabra, 210 miles

northeast of Madagascar, HO 3861, 18 by 7 miles, is a slightly elevated atoll, with a well dissected reef flat 1 or 2 miles wide and 20 feet high, and a shallow or dry lagoon. A channel, 9 to 12 fathoms deep, leads out to the northwest and suggests a short period of low-level erosion, such as a Glacial epoch might have afforded. This atoll has been examined by Abbott (1893), Voeltzkow (1901, 1907), and Fryer (1910–12). The last-named observer concludes, on what seems unconvincing grounds, that "all evidence gained on Aldabra and its neighbors points to a method of formation by elevation and not by subsidence, and Darwin's theory is therefore untenable" (p. 435); he also suggests, but like C. W. Andrews without inquiry sufficient to justify the suggestion, that the emergence of this atoll was caused by a general lowering of the ocean. Cosmoledo, HO 3861, is about 100 miles east of Aldabra, which it resembles. It has a 9-by-6-mile reef, of which the flat is from 1 to 1-½ miles wide, enclosing a lagoon 3 or 4 fathoms deep and surmounted by several limestone islands up to 55 feet in height. Niejahr (1876) reports volcanic rocks on Cosmoledo, but Fryer (1910–12) does not mention them.

Gardiner, who visited several of the above-mentioned elevated reefs on one of his Sladen-Trust expeditions to the Indian Ocean, concludes that the facts "indicate that these islets lie in a district which is by no means stable, by no means at rest, or subject to the same movement all over its area. The whole series of banks . . . may be regarded as occupying part of the site of the Indo-Madagascar continent. Yet, allowing this to be the case, we are seriously inclined to doubt whether its different reefs represent any peaks of that land, but are not rather the result of separate volcanic eruptions" (1906, p. 328). This aspect of the question will be taken up in Chapter XVIII, when the Maldive atolls are described.

Voeltzkow, whose studies were largely zoölogical, appears to have concluded that the slightly elevated atolls of this region rest upon a foundation of earlier and different origin: "Es wäre ja die Möglichkeit nicht von der Hand zu weisen, dass ebenso wie bei den Riffen des westlichen Indischen Ozeans, auch . . . [bei diesen Atollen] ein Gebilde älterer Herkunft als Sockel diene, das bei einem Rückzug des Meeres trocken gelegt, im Laufen der Zeiten durch die Gewalt der Wogen bis zur Flut-Ebbezone abgeschliffen, und dann erst von Korallen besiedelt wurde, dass also auch hier die Grundlage des Atolles ein älterer organogener Kalkstein mit weit zurückreichender Bildungsgeschichte sei, und ihm in neuerer Zeit als sekundäres Gebilde die jetzige Korallenrinde aufgesetzt wurde, die einen seit langen Zeiten andauernden ununterbrochenen einheitlichen Aufbau durch die Tätigkeit der Korallen vortäuscht" (1907, p. 32–33). In comment upon this statement, it may be urged that an emerged bank of limestone would be more likely defended by fringing reefs than abraded by the ocean waves and also that the older limestone foundation, on which it is thought this reef rests, may very

probably be a reef-flat limestone of earlier formation; for in such limestones recognizable corals are rare.

Uplifted Atolls in the Lesser Antilles

Three uplifted atolls in the Lesser Antilles, and hence belonging in the Atlantic marginal belt, should be recalled in the present connection. One is Marie Galante, a recently and evenly uplifted atoll; another is Sombrero, an evenly uplifted and little-dissected but rather strongly abraded atoll well described by Julien (1867); the third is Antigua, a tilted-up and beveled-off atoll, of which some account has already been given in Chapter VIII and of which I have elsewhere given a fuller description (1924, 1924a). A moderate measure of subsidence during reef formation is suggested by the first and second, but the measure is not complete because the foundation rocks are not there exposed. A much greater measure of subsidence during reef formation is demonstrated by the heavy limestone strata that rest on a volcanic foundation in the third, which thus becomes one of the most valuable witnesses for Darwin's theory of coral reefs that has been found in any ocean. A fourth West Indian example is Navassa, west of the southern arm of Haiti, briefly described by Schmidt (1921).

The Bahamas, Considered As Elevated Atolls

By far the most remarkable elevated limestone islands in the West Indies remain to be described. They are the limestone islands of the Bahamas, east of Florida and Cuba, HO 26a, b, c, d, 944, 948, which are here tentatively placed in the class of marginal-belt atolls now moderately elevated. Agassiz, who has given a detailed account of them (1894), recognized some sea-level reefs that may be regarded as true atolls, one of which will be described in Chapter XVIII; others that appear to be sunken atolls, some of which will be noted in Chapter XVII; still others that are slightly emerged and more or less abraded, as will be told here; and also a fourth or composite class.

Agassiz has published a colored depth chart of these islands (1894, Pl. 1): his views as to the origin of the islands are concerned only with the latest phases of their formation: he inferred that the surface limestones are of eolian origin, their materials being supplied from coral-sand beaches. "After the formation of the islands came an extensive gradual subsidence, which can be estimated at about three hundred feet, and during this subsidence the sea has little by little worn away the eolian hills, leaving only here and there narrow strips of land in the shape of the present islands. . . . My reason for assigning a subsidence of three hundred feet is that some of the deep ocean-holes on the bank have been sounded to a depth of thirty-four fathoms. . . . The present [sea-

level] reefs form but an insignificant part of the topography of the islands, and they have taken only a secondary part in filling here and there a bight or a cove with more modern reef rock" (1894, p. 7). This passage is of interest, as it is one of the very few in which Agassiz recognized the occurrence of subsidence: and here the "subsidence" may have been only a submergence due to the Postglacial rise of ocean level.

Vaughan's interpretation of the Bahamas agrees with Agassiz' in ascribing little of the surface rock to reef limestones but differs in several other important respects. The oölitic limestone of the islands is regarded as not of eolian origin but of chemical deposition on former shoals or lagoon floors and as therefore owing its present altitude to upheaval. This supports the origin of the islands as atolls. Vaughan writes: "Neither the Bahamas nor the oölite keys of southern Florida are coral islands. . . Elevated coral rock is exceedingly scarce in the Bahamas" (1913, p. 303). On Andros Island, lagoon oölites are several thousand times greater in volume than coral-reef rock (1914d, p. 27).

My own tentative interpretation of the Bahamas is based on the facts reported by Agassiz and Vaughan but includes also the possible action of low-level abrasion in the Glacial epochs as suggested by Daly. It assumes that in Preglacial and Interglacial times atoll reefs were here of normal development, presumably on subsiding foundations, and that the oölitic limestones which now make so large a part of the islands were then accumulated as lagoon deposits in the manner explained by Vaughan. It assumes further that the atoll rims then formed were very generally cut away by low-level abrasion in the Glacial epochs and therefore survive only in small volume today; also that the inward reach of abrasion then accomplished was relatively narrow, perhaps because the reef corals were killed by low temperature only for a relatively short time. Shallow banks exterior to the present reefs frequently fringe the island shores, as is seen on Andros Island, HO 26a, where the bank has a width of from 3 to 5 or 8 miles. This gives some support to the interpretation here proposed; but as the interpretation is framed largely in view of what has elsewhere been better learned regarding the features of the marginal belts, it should be tested on the ground—with the general theory of the marginal belts as well as the local facts in view—before it can deserve acceptance.

Summary

Elevated atolls offer much more extended surface for human occupation than sea-level atolls do and much safer surface too, for they are not subject to being overwhelmed by earthquake waves. Their reef rims are in some cases so steep-sided and so ragged as to be traversed with difficulty. Their central area, if undissected, is monotonously smooth; if dissected, impassably uneven. The phosphate deposits found on some of these islands are commercially valuable; their shipment is usually

attended with difficulty as the island shores are without good harbors. Most of the oceanic examples do not reveal their foundations or exhibit their structure; hence all the more attention should be given to the few that, like Eua, Tuvuthá, and the Exploring Isles, are more communicative. It is highly significant of the origin of the others, and of the origin of sea-level atolls also, that these few communicative examples are unanimous in testifying to the close association of foundation subsidence and reef upgrowth; significant also is the confirmation of this testimony given by most of the elevated atolls, such as Goram and its neighbors, in the Australasian archipelago; but the contradiction of this testimony by Roti and Barbados, and perhaps by Christmas Island also, must not be forgotten.

The evidence for Darwin's theory given by some of the elevated atolls of eastern Fiji is believed to be beyond refutation. The region has evidently long been unstable; it has clearly suffered diverse movements of upheaval and subsidence; and reef formation has been closely associated with the movements of subsidence. Moreover, the evidence there given for Darwin's theory was not obtained merely by searching for such evidence; it was obtained by working out the geological history of the region, in which the formation of coral reefs was seen to be simply one of a number of events, all of which had to be arranged in a reasonable order. When that order was found, it appeared that reefs had been formed wherever and whenever subsidence took place, essentially as Darwin had supposed; but it was also found that subsidence alternating with upheaval had been determined by the westward migration of a broad and low anticline, of which he knew nothing whatever. It may be further remarked that the competence of Darwin's theory in accounting for the various forms of reefs in the Fiji archipelago, in spite of its geological history having been much more complicated than Dana and Agassiz supposed and in spite of the rejection of the theory by most of the later students of coral reefs who have visited that archipelago, is greatly to its credit.

The complete inability of other theories to explain the Fiji reefs must not be overlooked. They have been accepted as competent, after what seemed to their inventors to be a sufficient examination. Hence it is not a little surprising to see how incompetent they become when they are cross-examined; that is, when a somewhat careful deduction of all their consequences, many of which were neglected by their inventors, makes it possible to test them impartially and strictly by confronting the deduced consequences with a large collection of pertinent facts. It then appears that the whole group of theories in which stationary islands are postulated must be set aside, because islands that are outspoken enough to give an account of themselves testify so generally for instability.

Particular attention should be given in this connection to islands that have experienced two movements; one downward when reefs grew up unconformably around them, the other upward when the compound mass

was elevated and revealed to our examination. When all islands of this kind, bearing unconformably elevated fringing, barrier or atoll reefs, as presented in the foregoing chapters, are reviewed, the body of evidence that they give for instability will be found weighty. That a large number of such islands should be found in the Australasian region of well demonstrated uneasiness is natural enough. That a moderate number of such islands should be found in the supposedly quiescent Pacific is instructive; for the quiescence of that vast region is thus shown not to be inconsistent with occasional downward and upward movements, presumably of slow rate. Darwin's theory thus receives strong support.

Addendum. The corniced shore lines on Vater Varâ (see page 451), reported by Andrews, especially those at mid-height, should now show a slight eastward slant, if the island were tilted to the west during its elevation, as in the middle block of Figure 212, and then set upright again, as in the foreground block.

CHAPTER XVII

SUBMERGED REEFS AND BANKS IN THE CORAL SEAS

Outline of Inquiry

The consideration of sea-level atolls is postponed until after an examination of such submerged reefs and banks as the coral seas afford, because one of the chief questions at issue regarding the origin of atolls is whether their foundations have long been stationary or have as long been subsiding; and on this question the features of submerged reefs and banks may throw some light. Let it be recalled that the term "bank" is here employed to name submarine shoals of moderate depth, whether rimmed or not, whose existence has been ascertained by soundings but whose nature and origin are not fully understood. Also that the term "platform" will be used only to name the nearly level but hypothetical surfaces of marine abrasion which have been thought by some students of coral reefs to underlie the smooth floor of reef-enclosed lagoons and of submarine banks, reef-rimmed or not. As already intimated, it is here believed that the smooth surfaces of banks as well as of lagoon floors in the coral seas are, as a rule, the product of submarine aggradation and that their smoothness has no necessary relation to the form of their foundation; but it is fully recognized that, where platforms have been prepared by low-level abrasion, bank sediments may be only veneers upon them, as is thought to be the case in the marginal belts of the coral seas.

Palawan and Its Submerged Barrier Reef in the Philippines

Just as the island of New Georgia in the Solomon group has provided the finest example of a raised barrier reef, so the island of Palawan, the long southwesternmost member of the Philippines, provides the finest example of a submerged barrier. The island, 240 miles in length by from 5 to 20 miles in width and 6800 feet high, is shown in its whole length on CS 4716 and in detail on eight other charts, of which CS 4316, 4317, 4321, 4323, 4325 are the most instructive. The shore line is well embayed, particularly in the middle and northern part of the west coast. There the large reëntrant known as Malampaya Sound possesses a shore line of marvelous intricacy, as shown on CS 4316, an excerpt from which is reproduced in one of my earlier papers (1918c, Fig. 10). The recency of the submergence by which this sound has been produced is indicated by its delicately pointed headlands and its minutely branching bays.

A well defined submarine bank, 20 or 30 miles wide and from 30 to 60 fathoms deep, borders Palawan along its northwestern side, facing the China Sea. The bank is itself bordered by a relatively narrow and dis-

continuous ridge, evidently a submerged barrier reef, with depths of 10, 20, or 30 fathoms along its crest and a rapid descent to deep water outside. Hence the bank must be interpreted as the lagoon floor for which the submerged reef formerly served as a sea-level barrier. Before submergence the lagoon had normal depths, such as 20 or 30 fathoms, in spite of the instability of the island that it bordered. The present shores of Palawan

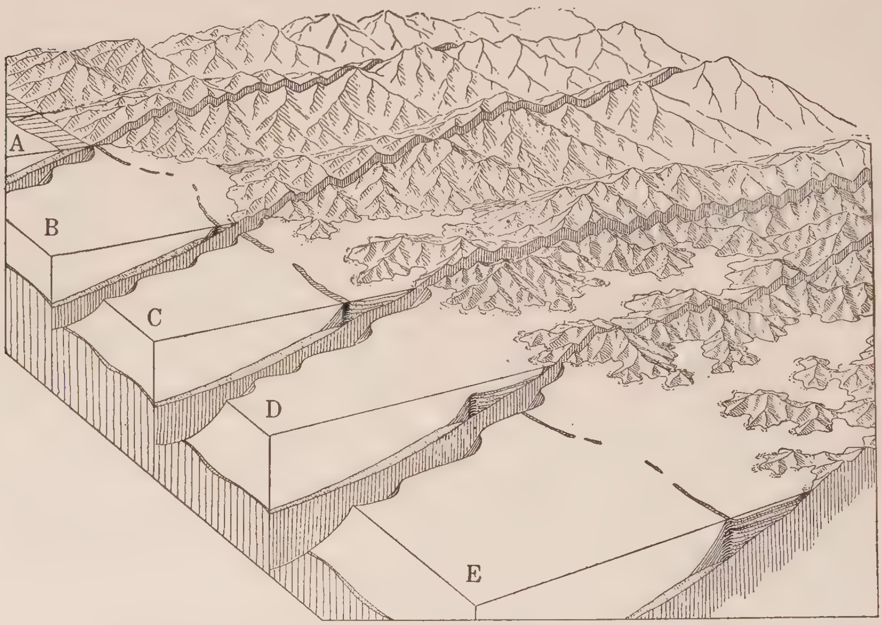


FIG. 215—Block diagrams, illustrating the development of the submerged barrier reef of Palawan, Philippine Islands.

are rimmed only by a discontinuous fringing reef of new generation; the fringe is 2 or 3 miles wide on Balabec island at the southwest end of Palawan, where the depth of the bank is 25 or 30 fathoms; but along much of the Palawan coast where the bank is deeper the fringing reef is narrow, and in certain stretches it is practically wanting. This is interpreted as meaning that the subsidence by which the barrier reef has been drowned was least and slowest and probably earliest completed near Balabec; and greatest and fastest and probably latest continued along the mid-Palawan west coast.

The sequence of developmental changes here inferred is represented in Figure 215. The background block, *A*, pictures a maturely dissected mountainous area, along the reefless shore of which an actively outwashed alluvial belt prevents abrasion. Subsidence then supervenes, embaying the main valley and permitting the upgrowth of a near-shore barrier reef, block *B*. Subsidence continues in block *C*, increasing the penetration of the valley embayment and the thickness and offshore distance of the

barrier reef. Then a rapid subsidence takes place, block *D*, still further enlarging the valley embayment and drowning the reef. This stage represents the mid-west coast of Palawan. It may well happen, in case the drowned reef still bears growing corals, that a continuation of slow subsidence will witness the upgrowth of the reef as a surface barrier again, as in block *E*.

The east coast of Palawan is usually bordered by a bank up to 25 miles in width, although no bank at all is charted for a short stretch near the island mid-length. The eastern bank does not, however, show a distinct reef rim. The geological study of Palawan has not been carried far enough to explain why the western bank should be margined by so good a reef rim, while the eastern bank is rimless; but it is probable that the two sides of the island have suffered different movements. In any case it seems safe to conclude that the western barrier reef was formed by upgrowth during the earlier and slower progress of a great subsidence by which, in its later and faster progress, the reef was drowned. Many minor oscillations may have taken place. The bearing of this on the instability of certain banks in the China Sea will shortly be considered. Northeast of Palawan are the Linapacan Islands, CS 4315, 9 miles across, over 1000 feet high, with very ragged outlines and narrow fringing reefs; they surmount a bank that measures 60 miles northwest-southeast, with a depth of about 40 fathoms. Like Palawan, these islands suggest recent subsidence, but their bank is not rimmed by a submerged reef.

It is interesting to recall that Darwin cautiously wrote concerning the sunken Palawan barrier and its enclosed bank: "Near the land this bank appears to be tolerably free from danger, but a little farther out it is thickly studded with coral shoals, which do not rise quite to the surface. . . . If these reefs of coral have a lagoon-like structure . . . they would have formed an imperfect barrier in front of Palawan. . . . But, as the water is not very deep, these reefs may have grown up from inequalities on the bank" (1842, p. 183), and the island coast was therefore not colored either red or blue. With the fuller information now in hand, such well balanced caution is no longer necessary. A belt of light blue, indicating subsidence, may now be confidently added to Darwin's map along the west coast of this long island.

Banks in the Sulu Sea

The small and deep mediterranean known as the Sulu Sea, CS 4200, well enclosed between the southern Philippines and Borneo, possesses two banks, Sultana and Kagayanes, each 18 miles long. They might be classed as imperfect atolls, because discontinuous marginal reefs reach the sea surface. Like the banks of the China Sea, next to be reviewed, these Sulu banks must, in view of the instability of the neighboring islands, be considered unstable; yet their depths are of ordinary measure.

The Banks of the China Sea

The Large Macclesfield Bank

The China Sea, a deep basin between the Philippine Islands and the coast of Asia, HO 796–799, contains a number of banks, the largest of which is Macclesfield Bank, HO 3167. It measures 70 by 35 miles. Several central soundings give depths of 50 or more fathoms; one of 60 fathoms is charted 9 miles from the western side of the bank. The bank border is a submerged reef, which usually has depths of 14, 12, or 10 fathoms and on which, according to the excellent descriptions by Moore (1889) and Bassett-Smith (1890, 1894), reef building corals and nullipores are growing. The latter observer states: "The amount of solid rock formed by vegetable organisms on this reef is . . . very large, and, as it was most abundant between 20 and 50 fathoms, its building-up power in such reefs as this must be a very important factor" (1894, p. 4). This goes to support the view above expressed that certain banks, either rimmed or rimless, have been significantly shoaled by aggradation since they were submerged.

The Macclesfield Bank as a whole is like a shallow, flat-bottomed dish with a turned-up rim. It may therefore be taken to be a drowned atoll of unusual size. Yet in spite of its depth being too great to be accounted for by low-level abrasion of a stable foundation, it is instanced by Daly as representing a former large volcanic island, similar in area and height to Hawaii, which remained stationary while it was dissected and degraded to a deeply weathered lowland with respect to normal ocean level in Preglacial time and which was then completely truncated by low-level abrasion in the Glacial epochs. The alternative possibility of instability and subsidence is not accepted, and the exclusion of that possibility is apparently thought to be justified by the general limitation of lagoon depths elsewhere to moderate measures. To my reading the position of the Macclesfield Bank in an Asiatic mediterranean would alone suffice to make a long stationary period for its supposed volcanic foundation extremely improbable; for great oceanic depths near a continent are strongly suggestive of recent depression. But wholly apart from that aspect of the case, the depth of 60 fathoms on this bank must be regarded as beyond the reach of low-level abrasion; all the more so when it is understood that, even according to the Glacial-control theory, the depth of the entire bank must have been significantly decreased by aggradation of the assumed subjacent rock platform during the Postglacial upgrowth of the reef rim. A platform of low-level abrasion, which when abraded must have had the form of a very low cone, cannot have been transformed into the shape of a shallow dish without some shoaling of the central area. It is therefore difficult to understand in what way this bank contributes any support to the Glacial-control theory. The evidence that it furnishes seems to me to be of precisely the opposite kind.

Smaller Banks in the China Sea

Several other banks of moderate depth occur in the same region, as shown in the table here presented.

SMALL BANKS IN THE CHINA SEA

HO CHART	NAME OF BANK	EXTENT (*miles*)	DEPTH (*fathoms*)	REMARKS
2786	Tizard	30 by 8 or 10	35 to 48	Discontinuous rim, ½ mile wide, 6 to 8 fathoms, bearing 8 reef patches
2786	Loaita	21 by 7	25 to 44	Discontinuous rim, 6 to 8 fathoms, bearing 7 reef patches
2786	North Danger	8 by 4	20 to 27	Continuous rim, 4 to 7 fathoms
2786	Thitu	7 by 3	16 to 19	Continuous rim, 6 to 8 fathoms, bearing 4 reef patches
797	Vanguard	32 by 7	23 to 57	Indistinct rim, 9 to 16 fathoms
797	Prince Consort	15 by 10	37 to 44	Rim 10 to 13 fathoms
797	Grainger	4 by 2	6 to 8	......
797	Alexandra	4 by 3	3 to 6	......
797	Prince of Wales	12 by 8	23 to 27	Rim 4 to 10 fathoms
797	Rifleman	29 by 13	30 to 45	Rim 5 to 7 fathoms
799	Luconia	35 by 15	......	Many reefs 2 to 5 fathoms
....	Palawan	8	31	Rim 6 to 8 fathoms

A number of these banks are, along with Macclesfield, included in Daly's tables from which, in view of their fairly accordant depths, it is concluded that the bank foundations have long been stable. It seems more reasonable, in view of the occurrence of the banks in a sea where the presumption of instability is strong and where no independent evidence of low-level abrasion is found, to conclude that fairly accordant bank depths can be developed by aggradation in spite of the instability of the bank foundations. This is particularly true in the case of the last-named bank, evidently a drowned atoll, which lies only 32 miles west of the submerged barrier reef of Palawan Island, above described. The recent reef-submerging subsidence of the island makes a similarly recent and rapid subsidence of the bank highly probable.

In the northern part of the deep China Sea, off Hongkong, is Pratas atoll, one of the finest examples of a sea-level atoll anywhere to be found; it is described in the next chapter. Farther south, off Hainan, are the Paracel reefs, HO 2785, with the great Macclesfield Bank beyond them. They include four good atolls: Discovery, 14 by 4 miles; Bombay, 10 by 3 miles; Money, 3 by 1½ miles; and Antelope, 3 by 2 miles; no soundings are charted in the lagoons. They also include two imperfect atolls: Amphitrite, 15 miles long; Crescent, 12 by 9 miles, a curved reef, open to the southwest, with a lagoon floor, 20 or 30 fathoms deep; also three reef

patches, 5, 7, and 8 miles long by 1 or 2 miles across; and, finally, the little Triton reef, hardly a mile in diameter, bearing a small sand islet; and Bremen bank, 12 by 3 miles, 10 to 13 fathoms deep, without a well defined rim. South of Macclesfield Bank is Scarboro atoll, HO 798, 8 miles in diameter. The association of these atolls with the banks listed above, strongly suggests that all have been developed over an unstable sea bottom. As none of them show any rock foundations, the volcanic islands on which their ancestral fringing reefs were in all probability first established have probably disappeared in consequence of subsidence.

The Deep Stewart Bank in the China Sea

Stewart Bank, 83 miles northwest of Luzon, northernmost and largest of the Philippine Islands, is of recent discovery by means of the newly devised echo-sounding apparatus. Being the first well certified example of its kind and therefore probably the precursor of others yet to be discovered, it deserves special consideration. It was found in March, 1924, when the U. S. Destroyer, *Stewart*, was steaming on a northwest course from Manila to Hongkong, over depths of from 1600 to 2100 fathoms. Soundings were being taken every 3 or 4 miles, when a rapid decrease of depth was indicated by more frequent soundings from 2140 to 332 fathoms in a distance of 9 miles. Next a fairly even space was traversed with depths decreasing from 332 to 240 fathoms and increasing to 300 fathoms again in 7 miles, after which a rapid increase in depth from 300 to 1700 fathoms was found in the 5 miles following. Then the *Stewart* made a sharp turn to the south and ran for 7 miles with decreasing depths to 400 fathoms at a point west of the shallowest sounding previously found on the northwest course. The vessel there turned east and traversed the bank again, finding a minimum depth of 160 fathoms near the bank middle and 342 fathoms at its eastern side, which was followed down for 2 miles to a depth of 1110 fathoms. Then a northwest course was resumed, the northeastern slope of the bank being traced with depths between 500 and 600 fathoms, until a rapid deepening to 1000 fathoms occurred in 2 miles and a slower deepening to 2100 fathoms in 13 miles. Similarly great depths were then continued. The entire maneuver occupied only four afternoon hours.

On the data thus secured and on record in the Hydrographic Office in Washington, I constructed a rough diagram of the bank (1925), here reproduced in Figure 216: the dotted parts of the contour lines are very uncertain. Previously charted soundings in the same region, HO 798, are: 2350 fathoms, 31 miles to the east; 1555, 11 miles south; 2171, 33 miles west-southwest; and 2095, 44 miles northwest. There still remains plenty of room in the China Sea without bottom soundings for the discovery of other deep banks; and it is therefore very probable that Stewart Bank is not the only one of its kind yet to be found there.

The origin of this bank as a reef-enclosed lagoon area is of course highly

problematic; but such an origin seems, in view of all the facts, more reasonable than any other that has been suggested. The bank was perhaps an almost-atoll, for one of the summit soundings, 160 fathoms, is 100 fathoms less than most of the others. As this is, except for the Saya de Malha bank, 60 to 200 fathoms deep in the Indian Ocean, the first fairly well defined bank to be found in the coral seas deeper than 150 fathoms, it has a large value in possibly corroborating an expectation based on Darwin's theory; namely, that some sea-level reefs should have been deeply submerged by an increase in the rate of the subsidence which had previously determined their formation. The bank has been discovered at, as one may say, the very outset of oceanic exploration by echo sounding, and has been found in a region so frequently traversed as the China Sea, where banks of less depth, most of which are named above, have been known for a good number of years; hence it is reasonable to expect that other deep banks will be found not only in that sea but also in the vast blank spaces of the Pacific, as echo sounding is further prosecuted.

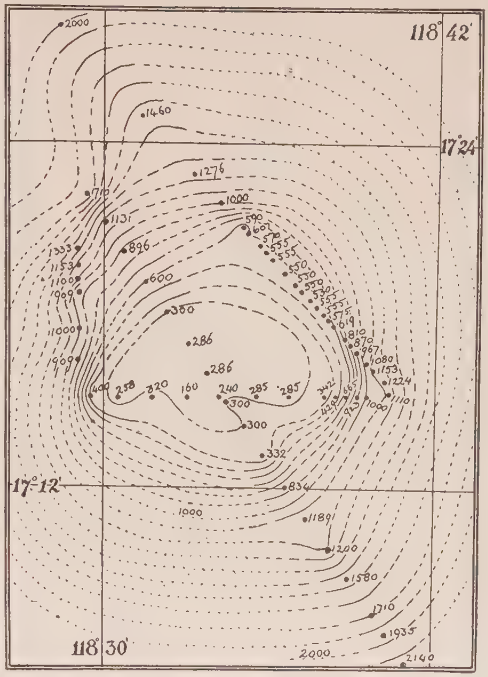


FIG. 216—Inferred contours of Stewart Bank, China Sea.

In view of all the facts of the case, including the manifest instability of the adjacent island of Palawan, it seems inadmissible to regard the deep basin of the China Sea as having been stable for the long time demanded by the Glacial-control theory in its explanation of the Macclesfield and other banks. Indeed, the question raised by Suess, "Ob nicht so wie die höchsten Berge, so auch die grössten Tiefen die jüngsten sind" (Vol. 3, Part II, 1909, p. 336), may be well applied here with affirmative implication.

Three Submerged Barrier-Reef Banks

The sunken barrier reef and its deepened lagoon floor along the southern coast of eastern New Guinea, which makes a good second to the sunken barrier off Palawan, has already been described in connection with its long sea-level stretches. It is probable that further surveys of the sea area to the southeast of New Caledonia will discover stretches of submerged bar-

riers and deepened lagoon floors in extension of the long sea-level barriers which, as now charted, there end rather vaguely. The submarine bank around Tutuila has been described in an earlier chapter as a drowned barrier reef enclosing a shallow lagoon floor These three examples all testify for instability and subsidence.

Submarine Banks in Fiji

The submerged northwestern extension of the barrier reef of Viti Levu and the deepened lagoon floor or bank that it encloses, already described in connection with the surface barrier reefs of Fiji, should be here recalled. They testify strongly against the stability of their region and thus contradict the evidence accepted by Daly as testifying for stability. The two soundings of 80 fathoms that are there charted beyond the outlying Yasawa Islands suggest the occurrence of a strongly submerged bank, which merits exploration if only in the interest of navigation; for it is eminently possible that submerged reefs of less depth may occur thereabouts.

A well defined bank of much smaller size extends, with a length of 12 miles and a breadth of 4, southeastward from the small island of Thikombia, the northeasternmost member of the group, Figure 34, 6 miles by 1, 630 feet high. The island is, according to information received by Agassiz (1899, p. 125), composed of limestone and is prolonged by a sea-level fringing-reef flat for 2 miles over the bank. The bank has a central depth of 50 fathoms; its marginal depth of from 22 to 40 fathoms may be regarded as a submerged and modified barrier reef.

A somewhat similar bank has already been described as extending with a width of 2 miles and a depth of 40 or 50 fathoms around the northeastern end of Taveuni (Fig. 102), while the southwestern part of the island, overwhelmed by volcanic outpourings, is reefless. Both of these small banks are decidedly deeper than lagoons of similar size generally are, and thus they suggest unusually rapid subsidence. In confirmation of this, it may be recalled that 10 miles northeast of Taveuni, Budd reef, already described as an almost-atoll, has a very narrow encircling reef and a lagoon with the unusual depth of 47 fathoms. These Fiji banks are so local and so exceptional and yet so much alike, that a similarly local and exceptional cause must account for both of them. The most likely local cause is an accelerated subsidence.

The account of the several subparallel belts of islands and reefs in eastern Fiji in Chapter XVI called attention to the five minute banks which there constitute the easternmost or Malan belt and explained them by the more rapid subsidence in a syncline which followed the anticline by which the limestone islands of other belts have been elevated. The occurrence of other submarine banks farther east than those of the Malan belt seems probable.

Submarine Banks in the Tonga Group

The most remarkable large submarine banks in the Pacific are those which, at depths of 80 fathoms or less, are surmounted on the north and south by the Tonga Islands, described in the preceding chapter. The banks themselves surmount a broad swell of the ocean floor that extends for some 600 miles with a northerly trend and a depth generally less than 500 fathoms. The swell is closely adjoined on the east by the great Tonga trough, with depths of over 4000 fathoms. This suggests the existence here of a vast crustal flexure of gentle deformation, between a broad swell or anticline on the west and a broad syncline or trough on the east. The Tonga banks are four in number, Vavau, Haapai, Namuka, and Tongatabu. Their over-all length is 160 miles, and their breadth is from 15 to 25 miles. They possess so many complications that only their leading features can be noted here.

The northernmost or Vavau Bank measures about 25 by 12 miles; its narrower northern end rises in the limestone island of Vavau, already described in Chapter XVI as the northern part of a supposed atoll reef rim. Farther south the bank has a series of narrow, 10-fathom shoals along its eastern margin, rising here and there in discontinuous surface reefs. Its broad floor shows a gradual increase of depth from 30 or 40 fathoms near the eastern margin to 80 fathoms near the western margin. There a decrease to 60 or 50 fathoms takes place, thus again suggesting the occurrence of a submerged and in this case a nearly obliterated reef, followed by depths as great as 500 or 600 fathoms not far beyond.

Smaller, irregular banks continue for 40 miles southward; between them the Tonga swell has depths of only 250 to 350 fathoms, until the Haapai bank (Fig. 217) is reached. It begins with small breadth on the line of the eastern or shallower side of the Vavau bank, then continues 35 miles with a gain of breadth up to 20 miles and with depths increasing from 20 fathoms on the east, where continuous surface reefs are well developed, to 87 fathoms near the western side, where, as on the Vavau bank, a marginal decrease to 60 or 50 fathoms is met with. The intermediate space is more beset with reef patches and bank atolls than is the case in the southern part of the Vavau bank. Some of the atolls are raised to heights of 60 or 100 feet. As far as they are charted the lagoon depths in the sea-level atolls are of normal measure, in spite of the manifest instability of the bank as shown by its westward slant.

A 3-mile passage with depths of 300 or 400 fathoms separates the Haapai from the Namuka bank (Fig. 217) which occupies a well defined area of 30 by 25 miles, again with linear shoals or surface reefs along the eastern margin about in line with those on the eastern margin of the more northern banks. A few reef patches and a few reefed islands, 100 to 160 feet high, rise from the middle of the bank, where the depth slowly increases westward until depths of 55 or 60 fathoms are reached along the

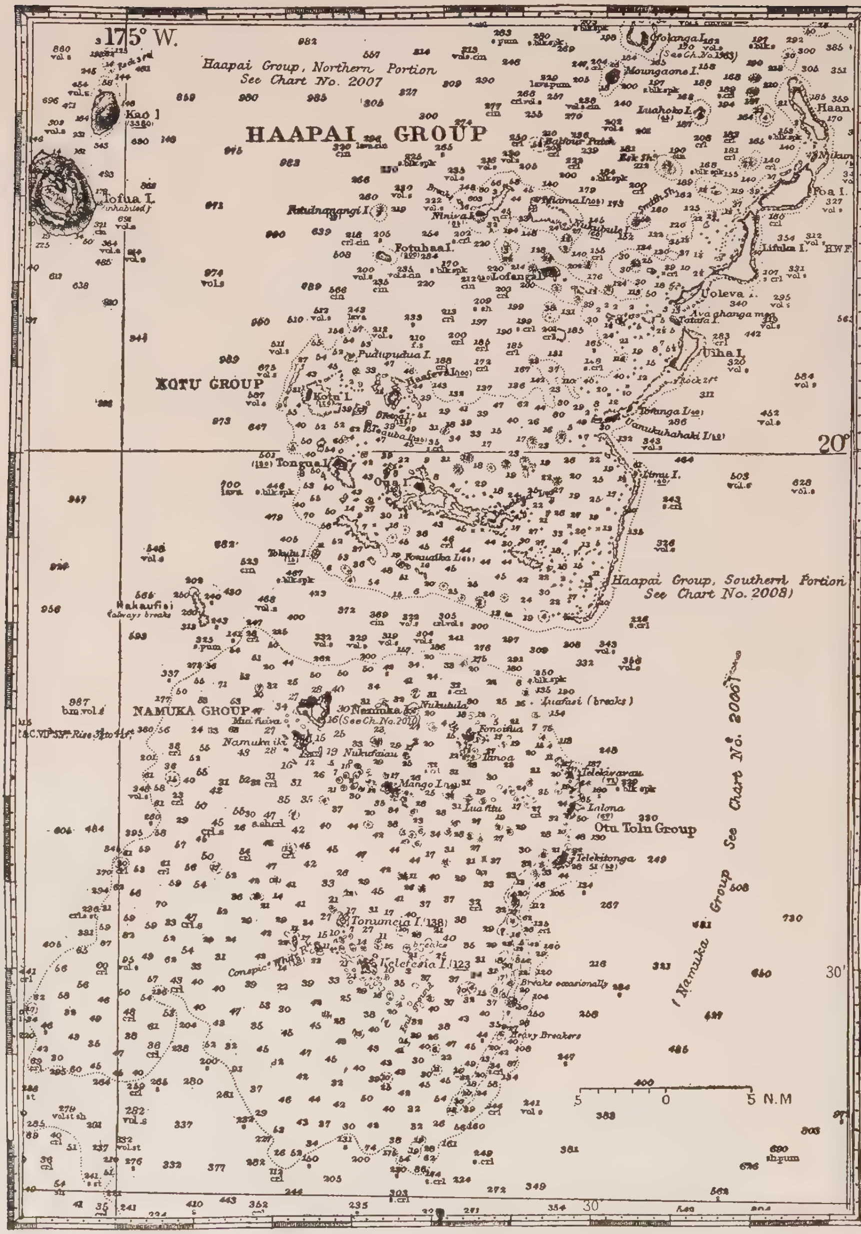


FIG. 217—Haapai and Namuka Banks, Tonga; HO 2016.

western margin. Then, south of a 5-mile passage, again 300 or 400 fathoms deep, comes the Tongatabu bank, measuring 30 by 10 or 15 miles, with depths of from 35 to 50 fathoms and for the fourth time with a narrow shoal or reef along the eastern margin. It rises southward to the limestone island of Tongatabu, the counterpart of Vavau. Depths of 150

fathoms or more continue beyond this island for a few miles and then increase to greater measures. The island of Eua, 12 miles southeast of Tongatabu, has been described in the chapter on elevated atolls.

It should be recalled that a series of young volcanoes, some of them active, is found in a well aligned belt 20 or 30 miles west of the Tonga banks, as has been told in the chapter on reefless volcanic islands. It was recorded by Sawkins (1856) that in 1854 an earthquake occurred in Tongatabu, "when the northeastern portion . . . was tilted down to an inclination sufficient to produce an encroachment of the sea for nearly two miles."

The following inferences, extended from those already noted in connection with the partly emerged atolls at the northern and southern ends of these banks, may now be drawn from the facts above stated. The four banks and the islands in which they end appear to represent four large atolls which have been warped in such a way as to rise above sea level on the north and south and become a little submerged with a westward slant in the intermediate area. As well as may be judged by the present depths of the banks and their marginal reefs, the former atoll lagoons had depths of 20 or 30 fathoms, which are normal enough for lagoons of their size, notwithstanding the presumable instability of the region during the time of their formation. In spite of the uplift suffered by the terminal islands, they do not, like the small neighboring island of Eua, reveal their foundation rocks; but whatever the foundation of the banks was, it may be supposed to have sunk as the atolls now represented in the banks were built up, just as the volcanic foundation of Eua sank as its terraces and crowning atoll were built up.

In addition to the warping of the former Tonga atolls into the terminal limestone islands and the intermediate banks, there must have been a small elevation of later date in order to cause the emergence of the now high-standing small atolls that surmount the banks; and, while those bank-surmounting atolls were forming, the banks must have been from 10 to 25 fathoms deeper than they are now. Both the earlier warping and the later elevation of the banks are probably to be regarded as minor manifestations of the continued flexure of the region, which may involve an eastward migration of the Tonga anticline. In this case the elevated Eua atoll would indicate the present position of the anticlinal crest, the tilted banks would be a little west of the crest, and the belt of active volcanoes would stand on the sinking rear slope. The adjoining syncline, rapidly deepening in front of the anticline, would determine the Tonga trough. This would repeat certain broad diastrophic relations that have been established in the East Indies and would give some support to the scheme of the westward advancing anticline in eastern Fiji, presented in the preceding chapter.

South of Tongatabu, 120 miles, a small, unnamed, 30-mile bank, HO 2016, has five soundings with the unusual depths of 93, 91, 89, 89, and 88

fathoms. Whether this bank is a volcanic summit that has never been built up to sea level or an atoll now submerged cannot be determined. If it prove to be the latter, it would be significant as a sea-level reef that has been lowered too far and too fast to maintain its crest at the sea surface. Similarly, 130 miles north-northwest of Viti Levu, Fiji, is another unnamed bank, HO 2021, with a single sounding of 85 fathoms. There is abundant room in the vast spaces of the Pacific where no bottom soundings have been made for dozens of small banks like these two to lie hidden.

The Darwin Hermatopelago

The most remarkable cluster of small banks, apparently drowned atolls, in the Pacific lies between the Fiji Islands and the Ellice atolls, in an area measuring 700 miles east-west by about 250 north-south and generally limited between latitudes 11° and 14° S. I have elsewhere proposed (1918c, p. 531) that the region of this cluster should be called the Darwin Hermatopelago, or Darwin Sea of Banks. The general charts of the region are HO 1993 and 2021; special charts are noted below. The banks are 19 in number and are here listed, beginning on the west.

The Darwin Hermatopelago

HO Chart	Name of Bank	Extent (*miles*)	Depth of Rim (*fathoms*)	Depth of Bank (*fathoms*)
1984	Hazel Holme....	5 by 4	17 to 20 on N	21 to 25
1984	Alexa..........	17 by 11	11 to 15	24
1984	Penguin........	7	16 to 20	25
1984	Turpie.........	23 by 12	15 to 20 on NE	27
1984	Louisa.........	?	?	?
1978	Whale..........	3 by 1	Rimless	15 to 20
1978	Rotumah........	4 by 3	15 to 20	25 to 36
1993	Bayonnaise.....	15 by 10 ?	Rimless	27 to 31
1986	Tuscarora......	9 by 6	Mostly rimless	24 to 31
1986	Adolph.........	1	Rimless	17 to 20
1993	Combe..........	11 by 5	Rimless	18
1986	Robbie.........	7	7 to 15	24 to 29
1986	Waterwitch.....	9 by 5	12 to 16	24 to 29
1986	Lalla Rookh....	4 by 2	Rimless	10 to 13
1986	Home...........	1	Rimless	10
1986	Field..........	7 by 3	Rimless	14 to 21
1986	Taviuni........	2 by 1	Rimless	9 to 12
1686	Pasco..........	20 by 14	7 to 12	22 to 27
2021	Isabella.......	2	Rimless	12

Many of these banks have not been well sounded; but those for which numerous soundings are charted have remarkably smooth floors within low and even-crested rims. According to the Glacial-control theory the submerged rims represent unsuccessful Postglacial reef upgrowths over abraded platforms: according to Darwin's theory, they represent sea-level atoll reefs which have been submerged by a broad and astonishingly even sinking of the sea floor hereabouts. It is difficult to conceive of any

method by which the truth of either of these explanations can be determined; but in view of the well warranted explanation for the origin of certain elevated atolls according to Darwin's theory in other parts of the Pacific, a similar origin for the banks is, to say the least, highly plausible.

It may be objected that, had the reefs once stood at sea level, they have now too uniform a depth for their submergence to be explained by a sinking of the sea floor, which ought, according to current geological views, to have sunk more unevenly. But to this it may be answered that, as the reefs really seem to have been submerged by sea-floor sinking, we must revise our views and measure the possible uniformity of such sinking by the uniformity of the reef depths. On the other hand, it may be objected that, had the reefs begun their upgrowth from low-level platforms, they could not all have ceased upgrowth at so uniform a depth; and to this it may be similarly answered that we must measure their uniformity of upgrowth by the accordance of the level that they had reached when some general calamity caused their upgrowth to cease. But a growth-stopping calamity is difficult to imagine in this region, in view of the thriving continuity of reef growth in the atolls of the Ellice group on the north and in the barrier and atoll reefs of Fiji on the south. However, aside from the great improbability that the processes of the Glacial-control theory have had any application in the middle of the Pacific coral seas, it is more difficult to conceive of a nearly uniform upgrowth of 19 independent reefs, each of which may have been subject to divers local accidents, than to conceive of a nearly uniform sinking of the heavy and quasi-rigid earth crust over an area of several hundred miles.

Islands Near the Darwin Hermatopelago

Rotumah and Its Submerged Reef

The volcanic island of Rotumah, HO 1978, 7 miles across, 690 feet high, rises in the southwestern part of the above described hermatopelago and northwest of Fiji. Its shore line is little embayed, perhaps because it is too young to have been dissected and submerged or possibly because any former embayments have been filled by recent lava flows, mentioned below. It is encircled by a submerged reef which seems to flank it on the south and east but which lies 3 miles offshore to the north and 6 miles offshore to the west at a depth of 15 fathoms. The bank or lagoon floor thus enclosed has a depth of 25 or 30 fathoms. Several small islands, largely composed of tuff with cliffed shores several hundred feet in height, rise from the submerged reef and exemplify the abrasive power of ocean waves where defending reefs are absent.

Rotumah has been described by Allardyce (1886) and Gardiner (1898, 1898a). The latter observer states that the island possesses no less than seven craters, from some of which "broad lava flows can be traced to the sea and along the beach, except where they are covered with a deposit of

beach sand; their angle of slope for 500 yards inland is rarely more than 3° or 4°. The coast is fairly even with a complete absence of the 'long points and deep fiord-like bays,' which, according to Dana, would on a volcanic island give indubitable evidence of subsidence" (1898, pp. 438, 439; also 1898a).

Darwin, in ignorance of the many drowned atolls above described, all of which seem to have been discovered since his time, treated Rotumah in an interesting way. He wrote: "From the chart in Duperrey's atlas, I thought that this island was reef encircled, and had colored it blue; but the Chevallier Dillon assures me that the reef is only a shore or fringing one" (1842, p. 162); hence the island was colored red, thus indicating that it was in a stationary or rising area, between the blue or subsiding areas of the Fiji Islands on the south and the Ellice atoll group on the north. But in the light of present knowledge, it is probable that whatever fringing reefs Rotumah possesses are of recent establishment on a young shore line of submergence. Hence, according to this interpretation, a blue color would have been justified on Rotumah and all over the adjacent hermatopelago, as well as over the whole Ellice group and over a great part of Fiji.

An instructive contrast is here presented between the banks of the hermatopelago as representing drowned atolls and Rotumah as representing a partly submerged barrier-reef island. The drowned atolls, if sufficiently submerged to prevent further reef upgrowth, are permanently lost unless they are later upheaved again or unless, if they remain stationary, they are built up by organic aggradation. But Rotumah, a barrier-reef island, also submerged sufficiently to drown its reef, is merely diminished in circuit and height and still offers good ground for the growth of a fringing reef of a new generation. Such a reef may be, if later submergence continues slowly, the precursor of a new barrier reef and eventually of an atoll. The force of the above contrast is weakened by our ignorance of the present state of coral growth on the bank reefs. It is, however, quite possible that many of them are occupied by living reef builders and that they may therefore rise to the surface again, if rapid subsidence is not renewed too soon.

The Horne Islands and Their Expected Bank

Northeast of Fiji, but not so far as the above-described hermatopelago, stand the two Horne Islands, HO 1986 (Fig. 218): Futuna, 10 by 3 miles, about 2500 feet high, and Alofi, 5 by 3 miles, about 1200 feet high. Their shore lines are sinuous but not well embayed. The islands are placed in the present chapter although no bank has been proved by soundings to exist around them, because of the strong presumption that a surrounding reef-rimmed bank must exist there. In view of their nearness to the Darwin Sea of Banks their recent subsidence is at least probable. Their form appears to be that of little eroded volcanic islands with non-cliffed

shores, according to the profiles given on the chart and reproduced in outline in Figure 218. It is, however, true that two observers have described the island as showing steep slopes. One was Wilkes, who briefly recorded that the slopes are "bold and precipitous" (1845, Vol. 2, p. 158). The other is Viala, a French physician officially resident on the barrier-reef

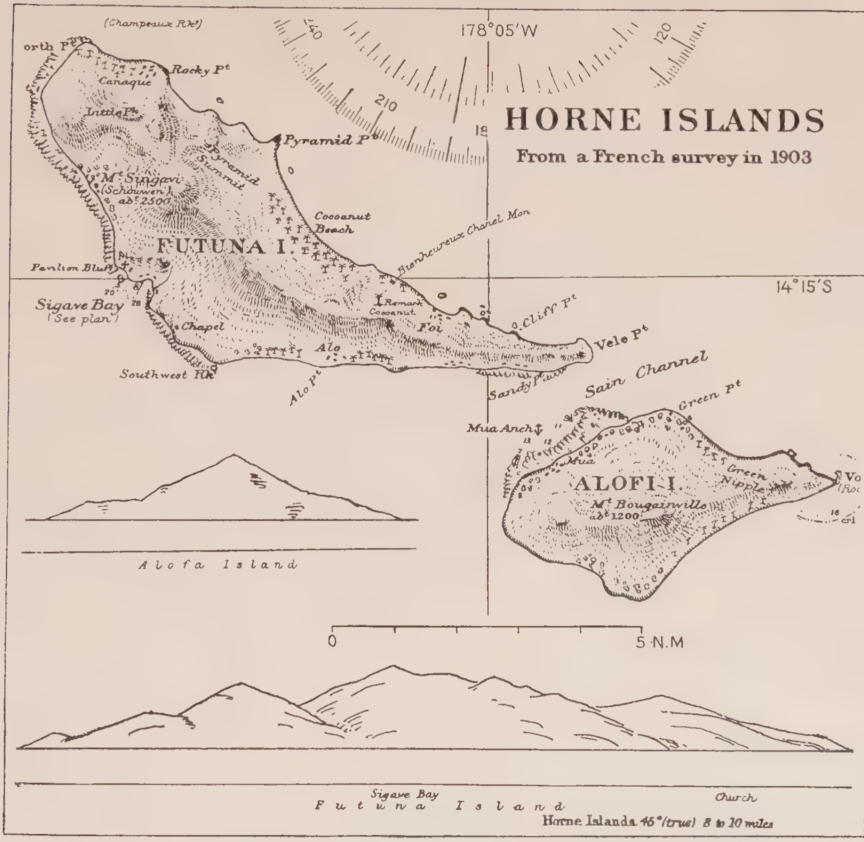


FIG. 218—The Horne Islands; HO 1986.

island of Wallis, whose descriptions show him not to be physiographically expert and who states with regard to the Horne Islands, which, like Wallis, are under French control: "Les flancs plongent dans la mer en falaises abruptes" (1919, p. 219); but he also compared the islands to pyramids, the characteristic feature of which is a uniform slope from summit to base, much as the profiles on the chart suggest. He adds that Alofi has caverns with stalactites and stalagmites; but whether these are tunnels in recent lava flows or solution cavities in the limestones of elevated reefs is not made clear. Inasmuch as the tendency of naval draftsmen is to exaggerate the slopes of mountain profiles and as, in spite of that tendency, the profiles of the two islands on the above-cited chart are of moderate decliv-

ity without indication of increased steepness near the shore, I am disposed to accept them as evidence that the shores are, as above stated, not cliffed. Less than a quarter of the island circuits is now fringed with reefs.

No soundings are charted around these islands, and hence it cannot be asserted that they, as well as Rotumah, are surrounded by a submerged barrier reef indicative of a recent and rapid subsidence of small measure. But in view of the non-cliffed island shores, it seems imperative that the islands were protected from abrasion by reef growth during whatever erosion their slopes have suffered. Therefore, following the example long ago set by astronomers in connection with great problems of vast spaces and more lately by chemists in connection with the systematic discovery of new elements, I am disposed to indulge myself, with regard to a remote matter of very small importance, in the risky pleasure of prediction. The prediction is that, when the waters around the Horne Islands are sounded, a submerged barrier reef will be found which, when at sea level, protected the island shores from abrasion.

Banks in the Caroline Group

A considerable number of banks occur in the Caroline group, as in the following table. All but the first-named are on HO 5417.

Caroline Group Banks

Name of Bank	Extent (*miles*)	Depth (*fathoms*)
Saijo	28 by 25	30
Gray Feather	40 by 25	40 or 50
McLaughlin	19 by 13	25 to 47
Condor	23 by 9	20 to 25
Uranie	19 by 6	24 to 33
Tarang	14 by 3	16 to 25
Earl Dalhousie	7 by 7	19 to 23
Gamen	14 by 3 to 5	

Manila bank in the same region is a submerged double atoll; the better-defined member measures 13 by 6 miles, with its reef at a depth of 6 or 8 fathoms and its lagoon 18 to 24 fathoms. The large atoll of Namonuito, not far distant, HO 5422, measures 40 by 30 miles, with the greater part of its reef at depths of from 3 to 7 fathoms and its lagoon 25 to 36 fathoms. Similarly, Los Martires, HO 1258, are the islets of an atoll 5½ by 4 miles across, with a lagoon from 10 to 20 fathoms deep, around which the eastern or windward half of the reef is submerged as if downtilted. The association of the above banks with these imperfectly submerged atolls is significant. Other apparently tilted reefs, the first three of which have been described in Chapter XIV, are: Mangareva almost-atoll, submerged around its southern arc; Yanaba almost-atoll, submerged in its south-western part; Hermit almost-atoll, in which the lagoon deepens to the northwest; and the large Menschikov atoll, submerged in its western part.

Banks and Atolls Northeast of Australia

The Coral Sea, so called from the large number of its atolls and imperfectly reef-rimmed banks, all of which rise from deep water, lies northeast of Australia between 13° and 22° S. It might be called the Australian Hermatopelago. It is a part of the Pacific coral seas, as defined in this volume; hence the incomplete reef growth on its banks must be ascribed to other unfavorable conditions than low ocean temperature. Tropical hurricanes are not frequent in the region; hence the failure of reef growth cannot be satisfactorily ascribed to an excessive stirring of bank sediments. Insufficient food supply can hardly be appealed to as causing the failure of reef growth, in view of the successful growth of many other near-by reefs. The Great Barrier Reef of Australia, not far distant on the southwest, and the well developed reefs of New Guinea on the north and of New Caledonia on the east should be here recalled. Recent and relatively rapid subsidence would seem to have been a more probable deterrent of reef growth in this Coral Sea than any other cause. Such subsidence is all the more probable because all that is known of the geological history of the surrounding lands suggests that they are only remnants of formerly still larger lands, which have been encroached upon by the sea in consequence of a relatively modern downwarping or downfaulting of the sea floor. The chief reefs and banks of the region as shown on HO 2002 and 2942 are, beginning on the northwest, given in the following table.

Reefs and Banks in the Coral Sea

Name	Extent (*miles*)	Depth (*fathoms*)	Remarks
Osprey atoll	15 by 5	19	Fairly good reef rim
Flinders atoll	20 by 15	33	Reef on SE
Holmes atoll	6	......	......
Frederick atoll	?	15 to 35	Reef on SE
Willis bank	13 by 15	20 to 30	Imperfect rim
Lihou bank	55 by 12	?	Discontinuous rim
Marion atoll	20 by 15	33	Rim on SE
Chesterfield bank	70 by 40	25 to 35	Discontinuous rim
Kenn bank	11 by 6	35	Imperfect reef on E
Saumarez bank	22 by 12	23 to 26	Imperfect reef on SE
Cato bank	11 by 7	30 to 36	Small reef on S
Mellish atoll	6 by 1½	Shallow	......
North Ballona bank	Not defined	?	......
Middle Bellona bank	Not defined	?	......
South Bellona bank	12 by 8	?	Reef on SE
Diana bank	12 by 8	14 to 23	......
Portlock reefs	14 by 6	......	......
Boot reef	9 by 4 or 5	......	......

In review, four groups of facts are to be noted. First, most of the banks have reefs on the southeast or windward side, where reef growth in sea-level barrier and atoll reefs is usually most vigorous. Second, the failure

of continuous reef growth does not seem to depend on bank depth; for Marion and Flinders atolls have depths of 33 fathoms in their lagoons, while Diana and Saumarez banks have depths of less than 33 fathoms. Third, the depths of the atoll lagoons are of ordinary measure, in spite of the strong presumption of instability in this region; hence the depth of both the lagoons and the banks has presumably been decreased by organic aggradation since their latest submergence. Fourth, the occurrence of these banks in a fairly compact group is suggestive of a broad and small, recent and rapid subsidence, thus repeating the cases of the China Sea, the Tonga Banks, and the Darwin Hermatopelago.

Fauro and Its Bank in the Solomon Group

Fauro, HO 2900 (Fig. 219), in the northwestern part of the Solomon group, may be taken as the type of an embayed and bank-bordered island without barrier reefs. It is about 12 miles in length and from 1 to 4 miles in width; its mountainous surface culminates in a peak 1825 feet in height; several other summits exceed or approach 1000 feet. Ovau, 2 by 4 miles, 1340 feet high, lies 2 miles northwest from the curved north arm of Fauro; a number of smaller islands and islets lie to the east and the southwest. The main island has been well described by Guppy as the remains of a greatly eroded volcanic mass; its complex structure is shown on a colored map; the smaller islands are presumably of similar origin. Guppy's description is in brief as follows: "So great has been the degradation of the surface that . . . here we have, in fact, the basal wreck of some huge volcanic cone" (1887, p. 33); again, in similar phrases: "Only the cores or 'necks' of the ancient cones remain at the present day" (p. 38); and "So great has been the denudation of the surface that we have nothing more than the cores or basal remains of the ancient volcanic cones, which have built up this island" (p. 40).

Not only has Fauro been greatly degraded; it has also suffered strong subsidence, as is shown by the sinuosity of its shore line, a sinuosity which was recognized by Guppy, although he did not take it as evidence of subsidence. He wrote on this point: "The irregular shape of the island, its deeply indented sea-border, and its numerous headlands, give it a large extent of coast-line in proportion to its land surface" (p. 32). No mention is made of shore cliffs in Guppy's text, and no indication of such features is given on the large-scale chart of the island, here reproduced in part in Figure 219. It bears no elevated reef but is usually bordered by a narrow fringing reef at present sea level.

The circuminsular bank is irregularly developed; it is hardly more than a mile wide on the southeast side of the island but expands to widths of 10 or more miles on the other sides; to the northwest it becomes confluent with a bank adjoining the much larger island of Bougainville. A discontinuous barrier reef reaches the sea surface near the bank margin south of

Fauro, and a discontinuous submerged barrier, with depths of 4, 6, or 8 fathoms, margins the bank east of the island; elsewhere the soundings near the bank margin, although often showing less depths than upon its

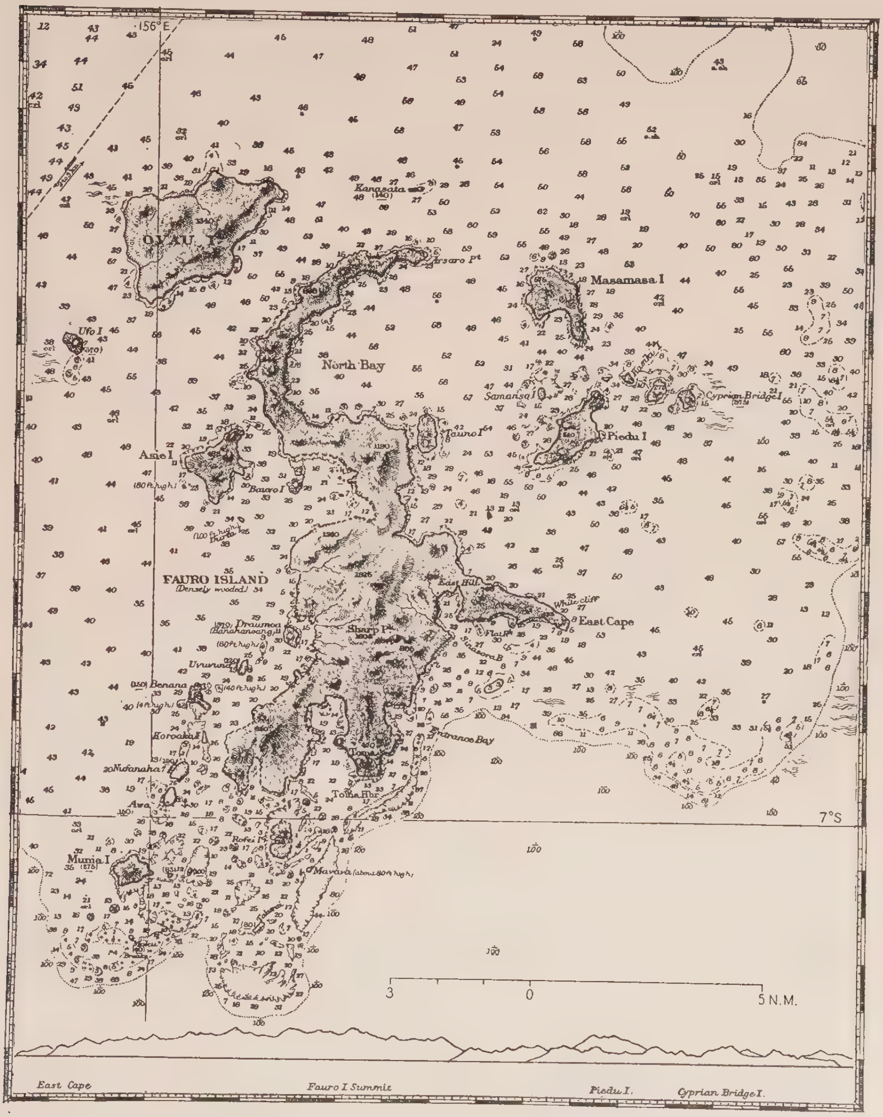


FIG. 219—Fauro and its bank; Solomon Islands; HO 2900.

inner area, do not clearly indicate a submerged barrier. The depth of the bank is generally 40 or 50 fathoms; but in an enclosed area between the curved northern arm of Fauro and the outlying smaller islands on the east, where low-level abrasion could not possibly have acted, a maximum depth of 58 fathoms is charted. To the east of those smaller islands

depths of 70 or 80 fathoms are given, with depths of only 30 or 20 fathoms beyond, near the bank margin.

There seems to be but one interpretation open for this island, its satellites, and its bank. It is as follows: For a time after their eruptive construction as a group of volcanic cones the islands stood at a considerably greater altitude than now and suffered long continued and severe degradation. The detritus discharged from them presumably prevented reef growth and permitted shore abrasion and must have shoaled the adjoining sea floor. During their degradation the islands began to subside, and the subsidence has now been so great that any shore cliffs which were cut in the preliminary reefless stage have been completely submerged. At an early stage of the subsidence the shore line was embayed and the detritus discharged from the valleys was detained in the bays. Then the development of an encircling fringing and barrier reef began; and the lagoon enclosed by it, measuring at least 20 miles across, was well aggraded as the reef grew up. At a late stage the subsidence became more rapid, especially on the northern side of the lagoon area; hence, while the southern turn of the reef still manages to maintain its crest at sea level and while the reef near by on the east remains as a submerged barrier, the reef on the north was well drowned and has been so far modified and obscured since its drowning that its earlier ridge-like form is no longer apparent. As far as may be inferred from the present depths of the bank, the lagoon floor that it is taken to represent was of ordinary depth before the recent acceleration of subsidence converted it into an imperfectly rimmed bank. The present fringing reefs of Fauro may be, in large part, regarded as of new generation.

As in all explanatory interpretations, hypothetical elements necessarily enter. Neither the preliminary construction of the Fauro cones by volcanic eruption, nor their severe degradation, nor their strong subsidence, nor the aggradation of the great area of the bank north of the islands inside of a barrier reef is a matter of observation. All are inferences. The first inference is based on the nature of the island rocks as well as upon the processes of volcanic action observed elsewhere. The second is based upon the form of the island surface as well as upon the processes of degradation observed elsewhere. The third is confidently based upon the pattern of the island shore lines, even though the actual production of embayed shore lines by island subsidence may never have been directly observed. The fourth is based upon the form of the surface reefs seen next south of the present islands as well as upon the known processes of reef growth and lagoon aggradation seen elsewhere. Thus the inferences seem to be reasonable. It may be objected, however, that, while no other process than volcanic eruption can conceivably have produced the islands, some other process than reef growth and lagoon aggradation may have produced the bank; and in our present incomplete knowledge of marine processes it is evidently the part of wisdom not to deny the possi-

bility of such unknown processes of bank production. But it should be remembered that, if such other processes dispense with a protecting barrier reef to enclose the area to be aggraded, the island shores should be cliffed; and they are not. The weight of the evidence therefore seems to lie on the side of the interpretation above outlined.

A submerged reef, 10 miles in length, crowned with growing corals at depths of from 3 to 8 fathoms and with deep water adjoining on the north, rises from the margin of the northwest extension of the Fauro bank, 10 or 12 miles northeast of Bougainville Island. It attracted the attention of observers on the German exploring vessel, *Gazelle* (1889, Vol. 3, p. 260), and it had been before their time instanced by Guppy as an example of a reef that was prevented by the power of the breakers from reaching the sea surface unless raised there by upheaval—an idea strongly discountenanced by Agassiz (1889, p. 143). In view of what has just been inferred as to the submergence of the former Fauro barrier, this submerged reef may be regarded as a less deeply submerged extension of it. Its occurrence in the neighborhood of an island crowned by a lofty and active volcano may go with the evidence cited in the account of Oahu in Hawaii to show that active volcanoes can be formed in regions of subsidence.

Submerged Reefs in the Dutch East Indies

It is remarkable that in the actively disturbed region of the Dutch East Indies relatively few submerged reefs and isolated banks have been charted. It is true that next north of the extensive Sahul Bank of the Arafura Sea northwest of Australia, 40 or 50 fathoms deep near its margin, a detached portion of the bank is found, BA 942A, 20 miles in length with the small depth of 14 fathoms. But other instances of this kind are rare. A few other banks of somewhat greater depth and therefore indicative of greater instability may be cited. One is in the deep Flores Sea south of Celebes; it surrounds the mountainous island of Tana Jampea, 12 by 5 miles, and a smaller island, 5 by 2 miles, 10 miles to the north. The bank is three times their area, with interior depths of 49, 50, and 56 fathoms and with smaller depths or minute reefs around its border. This clearly suggests a submerged barrier reef. Several sea-level atolls lie not far away.

The second example is east of Gilolo, the irregular island that imitates Celebes on a smaller scale: it is an unnamed bank, Dutch chart 389, 26 by 11 miles across, generally from 30 to 60 fathoms deep but with two soundings 101 and 103 fathoms; its marginal depths are from 7 to 14 fathoms. Two small islands of undefined form rise from the bank to heights of 80 and 190 feet; whatever their form before the reef was submerged, they are probably cliffed now. The bank therefore seems to be a drowned almost-atoll. The third example is of large area: it includes the bank and submerged reefs adjoining the islands of Waigeo and Batanta, which lie

northwest of New Guinea, have been described by Wallace and are shown on HO 2978; the first measures 60 by 30 miles, 3142 feet high; the second, 30 by from 4 to 6 miles, 3511 feet high. Both are well embayed, indicating subsidence after advanced dissection; both have sea-level fringing reefs; both rise from an extensive bank which occupies the 15- or 20-mile space between them, where the midway depth is from 66 to 79 fathoms. The bank extends 10 or 15 miles west of Waigeo, with depths of from 60 to 71 fathoms; its margin is marked with discontinuous stretches of sunken barriers; it must have been of ordinary depth before the marginal reefs were submerged. Farther southwest, near the Jef Fam Islands, which seem to rise from a west-slanting, raised almost-atoll, is a bank, 6 by 3 miles, with central depths of 42, 53, and 54 fathoms and a shallower rim; it seems to be a drowned atoll. In the same district, Groot Fam is a skeleton island, 4 miles across, 702 feet high, surrounded by a bank a mile wide and 50 or 60 fathoms deep, probably representing a recently submerged, close-set barrier reef.

In view of these various indications of submergence the inference seems unavoidable here, as off Palawan, that the great bank adjoining Waigeo and Batanta represents a depressed lagoon floor of large area, imperfectly enclosed by a barrier reef which grew up during the earlier and slower subsidence of the islands and which was drowned by their later and faster subsidence. Darwin must have had very incomplete information about this region; he only noted that considerable parts "of the northern shore of these islands are seen in the charts . . . to be fringed by coral reefs" (1842, p. 172), and they were therefore colored red. But the fringing reefs are evidently of a new generation following the drowning of the earlier-formed barriers. If the charts to which he had access had shown the facts as we now see them, he would undoubtedly have recognized these fringes as new reefs which had become "attached to the land" after "an old barrier reef" had been submerged by rapid subsidence (1842, p. 124), and he would therefore have colored Waigeo blue.

A Deeply Submerged Reef in the Ceram Sea

The record of a remarkable dredging made in the Ceram Sea, a deep basin in the Molucca island group, by the Dutch Siboga expedition and described by Weber (1902, pp. 80, 81) is here significant. The dredge was dragged for three miles, beginning at 893 fathoms and ending at 711 fathoms, at a part of the sea where the nearest sea-level reef is 30 miles distant. Many fragments of reef-building corals were brought up; they were several inches in diameter, somewhat worn, and covered with a layer of manganese oxide. Molengraaff calls attention to this remarkable haul, which may truly be regarded as one of the most instructive yet made in deep-sea exploration. He interprets it as indicating a strong and recent downwarping, probably compensated by upward movements in the

neighboring islands (1916, p. 229). This is reasonable, because strong and recent warping is abundantly indicated by the geological history of the Dutch East Indies, as is pointed out in one of my earlier papers (1918b, p. 391). It may therefore be inferred that the rarity of submerged reefs and banks on the charts of this region is in part at least because such reefs

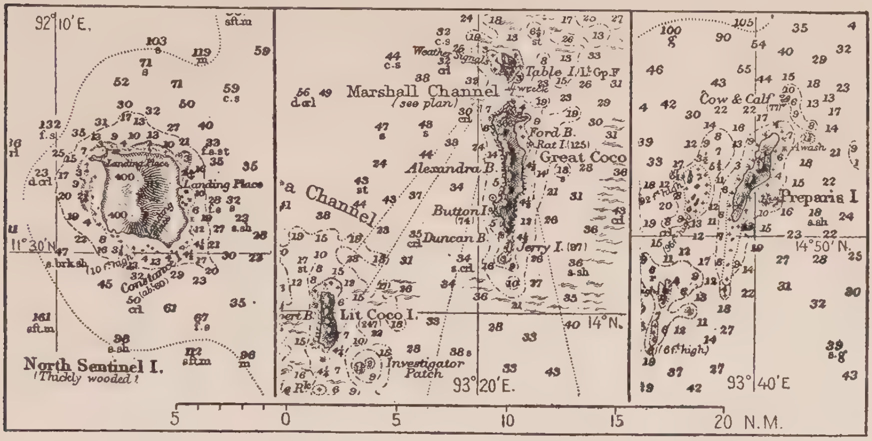


FIG. 220—Small islands and banks near the Andaman Islands; BA 825.

as once existed there have been submerged to depths so great that they have not yet been discovered.

The Andaman and Nicobar Islands and Their Banks

General Account

The Andaman Islands in the southeastern part of the Bay of Bengal and the Nicobar Islands farther south are composed of deformed and greatly eroded continental rocks and appear to be the non-submerged parts of an elsewhere submerged mountain range which follows a curved course from the embayed coast of western Burma on the north, already described, to a chain of islands near Sumatra on the southeast. The main member of the Andamans, BA 825, 125 miles long, 10 or 15 miles wide, and with heights from 1600 to 2400 feet, is divided by two narrow channels into North, Middle, and South Islands, on which the ridges have well marked north-south trends. The shore line is elaborately embayed; some of the transverse bays are 2 or 3 miles wide at the mouth and ramify into the islands in a manner implying a rather strong submergence after mature erosion.

The spurs of the larger islands decline to sea level without cliffs; the same is true of the slopes of the smaller islands, as may be seen in Figure 220. The non-cliffed shores of the large islands, if not reefless, are bordered only with narrow fringing reefs. Slightly elevated fringing reefs and beaches are reported. Banks with marginal depths of 40, 50, or 60

fathoms are well developed around the main islands to a width of from 2 or 3 to 20 or 30 miles. Detached banks of small or intermediate size occur around the little outlying islands. No other oceanic island group presents so fine a combination of non-cliffed spur ends and intricate embayments with well developed but not reef-rimmed circuminsular banks.

The Nicobar Islands, HO 3736, are nine in number and occupy a belt 165 miles in length. The largest island is 28 miles long, its greatest height is 2105 feet. The shore lines are embayed to a less extent than those of the Andamans; fringing reefs occur on the salients, and alluvial flats occupy the reëntrants. Elevated reefs are reported up to 80 feet above sea level. Banks lie around and between the islands, but their margins are not well defined by the charted soundings.

Accounts of these two island groups have been written by Rink (1847), von Hochstetter (1864–66), Stoliczka (1868), Oldham (1885), Cadell (1889), Chun (1900), Kloss (1903), and Tipper (1911). Few of these observers give close attention to coral reefs, and none of them give critical consideration to the points here under discussion; physiographic arguments are little employed. Von Hochstetter, an early and widely experienced observer, thought (1864–66, Vol. 2, p. 83) that the uplift of the Nicobars was caused by the eruption of gabbro and serpentine masses, but he drew no inference of submergence either from the strong unconformity that exists, according to his sections, between these igneous rocks and the much younger coral limestones or from the irregularity of the island outlines. Neglect of the latter feature is the more singular, as this distinguished geologist was one of the earliest explorers to make application of Dana's principle concerning the origin of embayments; for he had previously recognized (1863, p. 40) that only by submergence can the irregular outline of the slender, northwest arm of the North Island of New Zealand be accounted for. But in this neglect he has the company of most if not all of his above-named successors.

It might be supposed, in view of the composite structure of the Andaman Islands, that the banks around them occupy bent-down and submerged land areas covered with outwashed detritus, as is very probably the case along part of the mountainous continental coast of Burma to the north; but for the Andamans it may be better supposed that the circuminsular banks have been reef-enclosed for most of the time since the first submergence of the islands, and that they were once maturely aggraded lagoon floors. The absence of shore cliffs, which proves that abrasion has not recently acted on the islands, especially on the little islands that rise from detached banks of small area, and the completeness with which the detached banks are built up to ordinary depths around the outlying islands, without significant aid from abrasion, speak strongly in favor of the second supposition above. It is not conceivable that the subaerial detritus washed out from the little islands would alone suffice for so con-

siderable an area of bank building as has here been accomplished; and it is quite impossible that such islands could have escaped being strongly cliffed and perhaps reduced to mere stacks, unless they were protected from wave attack by barrier reefs while the banks were forming around them.

Inferred History of the Andaman Islands

Thus conceived, the recent history of the Andaman Islands may be outlined as follows: They formerly made part of a continuous mountain range of greatly deformed structure and of deeply eroded form, which curved from Burma toward Sumatra. The island segment of the range was isolated by an unequal warping, whereby adjacent segments on the north and south were rather deeply submerged. The depression of those deeply submerged parts was so rapid that no coral reefs have been built up to sea level from them. The depression of the surviving Andaman segment also was for a time too rapid for reef growth: thus it was divided into a number of larger and smaller islands, each of which now has its own bank. Then the depression was, for a later time, slow enough for the upgrowth of a number of barrier reefs, whereby the island shores, progressively shrinking back and becoming elaborately embayed, were protected from abrasion. The reef-enclosed lagoons were eventually so much shoaled that, after an accelerated subsidence had drowned their reefs, the lagoon floors gained the smooth surface of the present banks; and this subsidence was so recent that little growth of new-generation fringing reefs has yet taken place.

The absence of all signs of submerged reefs around the bank margins is at first sight unfavorable to this explanation. But it may be not unreasonably supposed that the reefs are no longer recognizable there because their lagoons were so well shoaled during a stationary interval that they resembled the shallow, reef-patch lagoon of Vavitao in the Austral group of the Pacific today. Post-submergence aggradation would then have built up the shoaled lagoons into the actual banks of somewhat unlike depths. Rapid subsidence is, indeed, well attested in the Andaman-Nicobar region; for, unless the vanished segments of the mountain range between and to the north and the southeast of these islands had gone down quickly, its entire length should be crowned by reefs today.

No better example than the Andamans can be found to illustrate the transparence of the theoretical counterpart of a group of facts in contrast to the opacity of the facts themselves. The banks around the Andamans are merely banks to the exploring navigator and his sounding line. But in the imagination of the speculative theorist the banks are underlain by maturely filled, barrier-reef lagoon floors, built up unconformably on the submarine extension of the island rocks; the submerged floors are now moderately aggraded; the buried rocks are a part of a warped mountain range; and so on and on. Some such explanation is, indeed, compelled by the absence of shore cliffs on the central islands of the Andamans,

especially on the little islands. There is of course the possibility still open that some new explanation, yet to be invented, will succeed in accounting for the Andaman shore lines and banks better than the one here offered; but, until that invention is perfected and announced, the explanation above proposed may be regarded as at least competent if not assured.

FIG. 221—A tapering spur end, Mahe, Seychelles. (Outlined from photograph by Keller, 1898, p. 160.)

Bank-Bordered Islands of the Indian Ocean

The coral-sea area of the Indian Ocean possesses, apart from the Maldives and Laccadives, few islands, few atolls, and fewer barrier reefs; but in its western half it contains many submarine banks, some of great extent and one of unusual depth. A great part of the ocean is, however, unoccupied. Between Keeling Atoll and Australia, the solitary Maria Augustina bank, 14° S, 108° E, 35 by 10 miles, stands alone, without recorded soundings. Between the same atoll and the atoll of Diego Garcia, which is associated with the Chagos banks of the west-central area, is a vast vacant space without islands, reefs, or banks of any kind. Three bank-bordered islands in the western part of the ocean will be first described.

The Seychelles Bank

The Seychelles Islands, north of Madagascar in latitude 5° S, surmount one of the largest banks in the coral seas, HO 2809: it measures 200 by 80 miles. The chief island, Mahe, HO 2810, is only 14 by 2 or 3 miles across with a height of 2993 feet. Like several smaller islands near by, it is composed, not of volcanic rocks, but of granite. It is moderately embayed between tapering points, which are rimmed with narrow fringing reefs. Pelly (1865) and Wright (1868) have described the islands briefly. The latter said, without giving his reasons: "It is evident that the land is gradually subsiding." Coppinger calls attention (1883, p. 218) to the exceptional composition of these oceanic islands. Bauer gives chiefly petrographic details but includes also a view (1898, Pl. 11) of certain scarps of "granite" curiously fluted by rain rills, like limestone. Brauer (1896) illogically concludes that the fringing reefs of Mahe cannot have been formed during subsidence, because the island bears an elevated reef

80 feet above sea level. Keller (1898, p. 158) and Chun (1900, p. 426) also mention the occurrence of the elevated reef. The question thus arises whether the reported reef is really the rain-rilled "granite" scarp figured by Bauer, or whether the "granite" of that scarp can possibly be reef limestone. A lower emerged reef is well certified by Gardiner, as noted below.

One of Keller's plates (1898, p. 160), here outlined in Figure 221, shows a tapering spur advancing, uncliffed, into the sea. Gardiner (1906, 1907) does not mention the elevated reef as such but notes that Mahe exhibits "a line of precipices, arising at 150 to 250 feet above the sea, situated a quarter to a half mile behind the shore, and cut only where mountain streams descend. It so remarkably resembles a coast line that we are still inclined to believe that it was so formed, and that there has been a comparatively recent elevation of upwards of 200 feet" (1906, p. 457). He did not inquire whether the general carving of the now partly submerged island had taken place before or after the elevated coast line was formed, although he states that "the hills in the Seychelles are so deeply furrowed and cut up into sharp ridges that they bear striking testimony to the long period during which atmospheric agencies have been at work" (p. 457). The now-elevated coast line is therefore probably younger than the valley furrows. Inasmuch as the furrows descend below sea level in the embayments of the present shore line, as is shown in one of Gardiner's plates (p. 464) though not noted in his text, the island must now stand somewhat lower than it did during the long erosion period and higher than when the elevated coast line—or elevated fringing reef—was developed.

The same widely experienced explorer of the coral seas gives the following account of the great Seychelles bank. It "has an average depth of 30 fathoms. . . . An outer rim is indicated along the whole of its northwestern half by a series of shallow soundings, but to the southeast the depth does not markedly shoal." The north rim is covered with silt, by which reef growth is prevented, while elsewhere reef growth "must be exceedingly slow. . . . Strong currents sweep across it [the bank], and even during our visit, between the two trades in dead calm weather, the sea-water was always cloudy, so that, except in favored spots, corals could scarcely grow up into a reef" (1905a, p. 294). It is added that all the islands "were found to be formed of similar, coarse granites (or granulitic quartzes), with narrow, vertically extending dikes of fine grained black rock . . . along which the mountain streams have invariably cut their courses. . . . In places there is evidence of a recent elevation of more than 30 feet. On the island of Silhouette [12 miles northwest of Mahe, 2 miles across, 2467 feet high], Mr. Cooper in five situations found masses of coral rock, cemented on to the granite, at various heights between 15 feet and 30 feet above the low-tide level, and around the coasts of Mahe and its smaller islets there is evidence of a similar upheaval" (1905a, p. 294).

Evolution of the Seychelles Bank

The surrounding bank is equaled in area only by the Nazareth and the Saya de Malha banks, described below, among all the pelagic banks of the coral seas. Over its vast area of 200 by 80 miles, it is generally from 25 to 35 fathoms deep; its greatest depth, 40 fathoms, is not far south of Mahe. Several small atolls stand on its northern margin. The following suggestions are offered in explanation of its origin. The foundation of the bank may be regarded as a portion of Gondwanaland, which is believed once to have connected India and Africa. The absence of spur-end cliffs on Mahe and the other granitic islands, as well as the vast area of the bank, forbids the reduction of the islands from a formerly larger land area by low-level abrasion. As to the changes otherwise suffered, one may suppose that much of the Seychelles area consisted of rocks less resistant than the granite of Mahe and that those weaker rocks were gradually worn down to moderate or low relief, but not necessarily to a plain, while the whole mass long stood higher than now. Also that, during the progressive subsidence of the mass to its present attitude, the worn-down area, presumably encircled by a great upgrowing barrier reef, was slowly aggraded.

The present bank may well have been produced by a continuation of this simple process, often exemplified elsewhere on a smaller scale. But, when the surviving land area had been reduced to several small islands and the reef had become an enormous almost-atoll, some condition unfavorable to further reef growth appears to have been introduced, with the result of leaving most of the bank today without a rim. It seems possible that this unfavorable condition was the recent and short-lived greater subsidence which permitted the formation of the 80-foot elevated reef reported by several observers—or the 200-foot shore line noted by Gardiner—on the slopes of Mahe; for at that time most of the bank margin would have had a depth of 40 or 50 fathoms or more, and any reef-building corals previously growing there would have been drowned. If the recent subsidence were less in the north than in the south, that would permit the survival of the existing atoll reefs on the northern margin of the bank.

The more mature the barrier reef had become at the time when the short-lived subsidence drowned it—that is, the broader the reef flat and the more complete the conversion of the lagoon into a reef plain as the result of a prolonged still-stand—the less demolition of the submerged reef and the less aggradation of the lagoon floor would be required to convert such a reef plain into the existing bank. It should be noted that the material for the aggradation of so extensive a lagoon or bank was probably derived in large part from organic sediments of local origin on the bank area, as Vaughan has shown to be the case in the lagoons of the Florida and Bahama reefs (1914). It is worth remembering in this con-

nection that, if material for such aggradation comes chiefly from locally supplied organic sediments, the supply will increase at about the same rate as the increase of bank area. Hence a large bank would be aggraded in this manner about as rapidly as a small one. The present depth of most of the bank is suggestive of aggradation with respect to wave and current action at present sea level.

The above speculations succeed in accounting for the bank with due regard to all the recorded facts. So far as I have read, the combination of the various factors and processes here suggested has unfortunately not been considered by any observer on the ground. As in various other islands and banks, it is not possible to discover in the Seychelles any consequences of Glacial changes of ocean level.

Mauritius and Rodriguez

Mauritius, BA 711, 33 by 22 miles, 2711 feet high, lying about 110 miles east of the younger and somewhat larger island of Réunion already described, has been so greatly eroded that it preserves no semblance of its initial form of eruption. Its shore line is partly simple, partly well embayed, and has a fringing or a close-set barrier reef around most of its circuit. Darwin observed on the coast land "little hillocks of coral-rock, which are either the last remnants of a continuous reef, or of low islands formed on it. . . . They were nearly 20 feet high, about 200 yards from the present beach, and about 30 feet above its level. They rose abruptly from a smooth surface, strewed with worn fragments of coral. . . . They were divided into irregular beds, dipping seaward, in one hillock at an angle of 8°, and in the other at 18°" (1842, p. 55). This is one of the few instances in which the structure of an elevated reef has been noted. A French observer is quoted by Darwin regarding a more continuous elevated reef which encloses a shallow, lagoon-like depression behind it in another part of the island. Haig (1895, p. 470) mentions "a conglomerate of rolled basalt blocks and pebbles embedded in a matrix of coral limestone" in association with the raised reef, which Voeltzkow (1906) has also described. This elevated reef must have an unconformable contact with its strongly eroded foundation, although no observers on the island have called attention to that significant relation.

The island of Mauritius is unsymmetrically surrounded by a bank 20 or 30 fathoms deep, which extends 1 or 2 miles from the shore on the south and 10 or 15 miles on the north, where it bears two small islands; also a small submerged bank atoll, nearly a mile in diameter, its reef being from 7 to 10 fathoms under water and the lagoon having depths of 17 and 19 fathoms. The bank falls off rapidly into deep water. Some account of it is given in the *Gazelle* report (1889, Vol. 3, p. 179), and by Gardiner and Cooper (1907–09, p. 117).

Rodriguez, east of Mauritius, BA 715, 10 by 4 miles, 1300 feet high,

is described, in Maskelyne's account of its petrography, as scored by valleys which have been "engineered by brooks that find their way to the sea, and meet the innumerable little bays and inlets that indent its shores" on the north (1879, p. 296); and also, in Balfour's account of its botany, as spreading out at the base of its mountain slopes into "a large coralline limestone plain" on the south, the plain being sharply demarked from the volcanic rocks and containing many caves (1879, p. 290). The island has also been briefly but empirically described by Keller (1898). The chart of Rodriguez does not show a plain surrounding it but only an unusually wide fringing-reef flat which, although almost wanting on two east-sloping spur ends, attains the unusual width of 2 miles on the northwest and 3 or 4 miles on the south, where it is said to be dry in patches at low water of spring tides. A bank, imperfectly sounded, extends some 15 miles to the west. There can be little question that the reef-flat limestones rest unconformably on the submarine prolongation of the island slopes. As the breadth of the flat seems to be much too great for production since the Postglacial rise of the ocean to its normal level, it must be largely of Preglacial origin, and its overlap on the island slopes must be ascribed to an earlier subsidence of the island. The submarine bank may be a part of the flat that was worn down by low-level erosion.

The unsymmetrical position of Mauritius and Rodriguez on their banks recalls the unsymmetrical position of Panniet (Fig. 194) in the Louisiade Archipelago and of Aitutaki in the Cook group of the Pacific with respect to their barrier reefs. It may therefore be supposed that these two banks in the Indian Ocean represent former unsymmetrically developed barrier-reef lagoons, the reefs of which have been drowned by rapid submergence and the floors of which have been aggraded to the levels of the reefs. The absence of shore cliffs excludes low-level abrasion as an agency for bank production here.

The Chagos Hermatopelago

The Great Chagos Bank

The Great Chagos bank, BA 3 and 2899, is of special interest from having been taken by Darwin to represent a drowned atoll, on which upgrowth to sea level had been prevented by an unusually rapid subsidence. It measures 95 by 65 miles. The central lagoon area has the considerable depths of 47 and 50 fathoms, from which "small, steep-sided banks or knolls, covered with luxuriantly growing coral, rise." This central area is discontinuously surrounded by a bench, which has the exceptional width of from 5 to 12 miles and a depth of about 16 fathoms. The bench is in turn surmounted around its outer edge by a reef rim, "consisting of dead coral rock . . . with scarcely any live coral," about a mile wide and 5 or 10 fathoms under water, except for two islets, Eagle and Danger, which reach the surface in the western arc of the reef circuit.

Outside of the reef rim a rapid descent is made to deep water. The bank as a whole would therefore seem to be an atoll which has had two subrecent episodes of uppermost growth, each prompted by subsidence, and the two separated by a long still-stand pause during which the first-formed reef became an unusually broad bench. The second subsidence appears to have been followed, before its reef had gained so unusual a width, by a recent and rapid but small subsidence.

Smaller Banks near Great Chagos

Not far north of Great Chagos are five other banks: Peros Banhos, 18 by 13 miles, 25 to 40 fathoms deep, and with 9 miles of submerged reef along its southeastern side; Speakers, 23 by 12 miles, with a lagoon depth of 20 to 24 fathoms and a submerged reef rim 6 or 8 fathoms deep. Between the last-named and Great Chagos are three small banks: Blenheim, 6 by 2 miles, with reef awash and shallow lagoon; Salomon, 5 by 2 miles, with reef awash bearing several sand islands and a lagoon 17 fathoms deep; and Victory, 3 by 2 miles, a submerged rim 3 or 4 fathoms deep and a lagoon 18 fathoms deep. West of Chagos is Owen bank, 19 fathoms deep. To the south of Chagos is the small Egmont atoll, 6 by 2 miles, with several sand islets on its reef and a 10-fathom lagoon. Farther on is the larger Pitt bank, 30 by 15 miles, with central depths of from 15 to 20 fathoms and a shallow rim; and still farther south are five small banks, with depths, as far as sounded, of 6, 8, and 9 fathoms. The atoll of Diego Garcia, to be described in the next chapter, lies 70 miles to the east of these small banks and 30 miles south of Chagos.

Gardiner on the Chagos Banks

Regarding Salomon bank, information is given by Gardiner, who has conducted by far the most extensive studies of the various banks in the Indian Ocean. He states that "its present reef is extending outward on every side on its own talus" and that the steep pitch by which descent is made to the deep ocean floor is "simply the slope at which coral and other remains from the reef above come to rest in the water." Soundings at depths of 250 fathoms or more showed that "the bottom was smooth and barren; the lead constantly failed to bring up any samples. . . . Our evidence points to . . . the probability of considerable current being felt even at 500 fathoms" (1905, p. 571). Concerning the Chagos banks in general Gardiner remarks that the outgrowing edges are almost wholly occupied by nullipores and that corals are important from 5 to 30 fathoms. Their profiles have the usual gradual descent to depths of 30, 40, or 50 fathoms in from 200 to 600 yards, beyond which is a steep pitch to 120 or 200 fathoms and then a more gentle slope to deeper water. The steep pitch is again described as "a talus slope, built of the remains of reef organisms, swept out by under-currents from the reef above. At the bottom of this steep [pitch], the talus was found to continue outwards.

the individual fragments getting smaller and smaller for 1 to 2 miles. The bottom then gradually became smoother between the banks, until it finally resembled almost a hard cemented road. . . . It was quite clear that the bottom between the banks and the Chagos was everywhere current swept even down to 1000 fathoms. . . . On the whole we are inclined to consider that the present banks of the Chagos were formed in a similar manner to those of the Maldives [to be described here in the next chapter], by a cutting down of a land by the action of the seas, and by the subsequent upgrowth of coral reefs as the currents moderated. Subsidence may have taken a part in perhaps paving the way for this action, but in any case we can have no doubt of the importance of erosion in the past and the present day in shaping the archipelago" (1906, pp. 323–325).

It is venturesome for one who has had no experience in deep-sea exploration to differ from a widely experienced expert in such work; but the attribution of not only a sweeping but also an eroding power to currents down to depths of 1000 fathoms goes so far beyond generally accepted views as to make its acceptance difficult. What the motive force for such currents can be is not clear; but if the currents are present the force must be found. On the other hand, it seems worth while wondering if the bareness of the deeper slopes may not represent initial lava beds, upon which no coarse reef detritus has ever been deposited and from which only pelagic ooze has been swept away. The suggestion that reefs have grown up where erosion formerly prevailed because the currents have now moderated their flow, can hardly be accepted without more direct evidence in its favor than is above presented.

Daly on the Chagos Bank

Daly has suggested that "mud-control may have an important bearing on the abnormal condition of Great Chagos . . . and some other banks"; that is, that upgrowing corals would "tend to suffer from occasional clouds of sediment washed up from the lagoon floor by major storms" and that the failure of the Chagos reef to reach the surface is therefore better explained by this control than by the rapid subsidence suggested by Darwin. Also that "subsidence would have to be incredibly uniform over a vast area, to explain the nearly uniform depth of the present rim on all sides of the bank" (1915, pp. 212, 213). But it may be urged, on the other hand, that it would be equally difficult to explain, first, the uniform surface of the broad, 5-to-12-mile bench, and, second, the similarly uniform crest of the higher rim by uniformity of submarine upgrowth from a stationary foundation: and, surely, pauses in the Postglacial rise of the ocean cannot be here appealed to in explanation of those uniformities, for in that case all the reefs of the coral seas should be benched like the Chagos reef. Reef upgrowth from an intermittently subsiding foundation with the limitation of such upgrowth by the maintenance of the reef crest at or close to sea level seems the better explanation. Be it noted further

that it would be difficult to account by low-level abrasion for a platform lying below the 50-fathom central depth of the Chagos bank unless subsidence had taken place afterward.

Truly, the uniformity of the latest supposed subsidence here is remarkable, for it submerged neighboring smaller banks also and thus extended over a much larger area than that of the Chagos bank alone. But the uniformity of subsidence need not be so perfect as the charts of Darwin's time indicated, for on the northwest of Great Chagos where a few islets occur the rim is only 5 or 10 fathoms deep, and on the southeast where there are no islets the rim is 15 or 20 fathoms deep. Finally, even if it be possible for clouds of sediment to kill reef-building organisms while their reef has little height over the bank from which the sediment is raised, it also seems possible that if a reef once succeeds, as the Chagos reef did, in gaining and long maintaining a height of 200 feet over its lagoon floor, its corals will thereafter have a good chance of continued growth, even if clouds of sediment are sometimes stirred up in the lagoon by storms. It should be remembered that in spite of the occasional turbidity of the Maldive lagoon waters caused by gale-driven waves, the corals still thrive on the surrounding reefs.

Banks in the Western Indian Ocean

Various Small Banks

A number of small banks in the region west, north, and east of Madagascar may be briefly described, as shown on HO charts 854a and b, 855a and b. Two banks lie 60 miles west of the north end of the great island: Leven, 30 by 20 miles, from 17 to 35 fathoms deep; and Castor, 15 miles in diameter, from 7 to 30 fathoms deep, with an ill-defined margin. North of the great island and about 50 miles west of the Seychelles are Platte Island and La Perle reef, both of small size and partly submerged. Southwest of the Seychelles is the Amirante bank, 85 by 10 or 20 miles, which has been described by Coppinger (1883), Gardiner (1906), and Gardiner and Cooper (1907–09). It has a smooth central surface about 30 fathoms deep and a rim rising to from 22 to 12 fathoms, with living corals and 21 low, reef-flat islands; hence it might be described as an imperfect atoll. Fifty miles farther south are the François and Alphonse banks, with some small reef islands. In the neighborhood of Farquhar Island, a somewhat imperfect atoll between the Seychelles and Madagascar, the chart shows: the Wizard breakers; an unnamed bank, 25 by 5 miles, bearing two small islands; Umzinto bank, . . . miles, 11 fathoms deep; and St. Pierre, a minute island. South of the Seychelles lies a narrow bank, 30 by 5 miles and from 11 to 25 fathoms deep; also Coetivy Island and two small 11-fathom banks. Farther east is Fortune bank, 35 by 20 miles, from 9 to 18 fathoms deep. The small inequalities of bank depths here found recall the small inequalities in the depth of the

Chagos bank rim. If that rim has been slightly tilted in its small subsidence, a similarly uneven subsidence may have taken place here.

The Nazareth Hermatopelago

A pronounced rise or swell of the sea floor, almost as extensive as Madagascar, is charted to the southeast of the Seychelles; it supports a number of banks, some of them of large size. The above name is suggested for this region in the lack of any other. The swell bears, first, an unnamed bank, 75 by 20 miles, from 5 to 40 fathoms deep. Then comes the large Saya de Malha bank, HO 3850, 120 by 140 miles and hence equal in area to the Seychelles bank, mostly 40 or 50 fathoms deep, with a broad submerged reef 5 to 15 fathoms deep on the northeast border and with depths of 100 fathoms or more in the south. The maximum depth of this bank is evidently too great to have been produced by low-level abrasion on a stable island: however formed, it would seem to have been very gently tilted. Farther south still lies Nazareth bank, 220 by 60 miles, from 18 to 40 fathoms deep; this merges southwestward into Carcados Carajos bank and reef, of somewhat smaller size near the end of the sea-floor swell.

Gardiner describes the Saya de Malha bank as consisting of three parts: a northern, a very large central, and a small southeastern part. The northern bank was "found to be separated by a channel of 636 fathoms from the central, while the depth between the latter and the southern bank is only 130 fathoms. All are of more or less atoll form, but the south side of the central bank differs from all other parts of the same banks and from the Nazareth Bank in tailing off very gradually from 65 fathoms, the general depth in its center, to 200 fathoms. The area in this part beyond 120 fathoms . . . formed a rich collecting ground, the bottom being composed of a white rubble of bivalve and sea-urchin shells, evidently all swept off the shallower bottom above. From 80 to 100 fathoms, where it is more exposed, the bottom is hard, being swept bare by the currents, but still further north at 60 fathoms, where the eastern edge of the bank has only 10–20 fathoms of water, is soft mud with casts of pelagic foraminifera" (1905a, p. 44).

Regarding Carcados Carajos, the same observer reports that it has "a crescentic-shaped surface reef, 31 miles long, on the south part of the Nazareth Bank, which is roughly 220 miles long by 60 broad, with an average depth of 33 fathoms." Near this surface reef the bottom has "a wonderfully constant depth of 30–35 fathoms over the body of the bank, while towards its western edge there is a slight but uniform rise to 27 fathoms, thus suggesting an incipient atoll with its eastern side slightly tilted up above its western. . . . The absence of living corals from the rim as well as from the plateau in all depths over 20 fathoms was a noticeable feature" (1905a, p. 44). The alternative of considering this bank a decadent atoll, with its western side a little depressed by unequal

subsidence below its eastern is not presented: nor is the indication of an unequal subsidence in the Saya de Malha bank given the emphasis that it seems to deserve. It is of course possible that this great bank, as well as others of less size, has been produced in some manner altogether independent of coral reefs; nevertheless, some association of banks and reefs seems probable. In any case, it appears to me altogether unreasonable to regard this bank region as stable.

Réunion, Mauritius, and Rodriguez islands lie on a nearly east-west line to the south of the Nazareth Hermatopelago. The last two islands have been described above as bordered with rimless banks and as thus resembling marginal-belt islands; but they are regarded as belonging in the coral seas of the Indian Ocean because they do not stand so far south as the usual southern limit of those seas elsewhere, because their shores are not cliffed, and because rimless banks are of so common occurrence in their ocean.

Much farther north, beyond the Laccadive atolls, are three rimless banks: Padua or Bassas de Pedro, 65 by 10 or 15 miles, 25 to 35 fathoms deep; Cora Divh, 20 by 6 miles, 25 or 30 fathoms deep; and Sesostris, 10 by 16 miles, 18 to 30 fathoms deep. Taken alone, these banks might be treated as having long had stable foundations; but, when associated with the Laccadive and Maldive atolls, the instability of which will be discussed in the next chapter, the banks are better regarded as having unstable foundations in spite of their accordant depths.

The exceptionally great depths found on a few of the above-mentioned banks explains why the average depth of 22 rimless banks, as listed in Daly's tables (1915, p. 192), is somewhat greater than that of reef-rimmed lagoon floors. That author holds that the excess of bank depth satisfies a demand of the Glacial-control theory; but it satisfies a demand of the subsidence theory just as well, for under that theory rimless banks are supposed to have subsided faster and lagoon floors rimmed with sea-level reef slower than the rate of reef upgrowth. Hence, like the decrease of lagoon depth with decrease of lagoon diameter, this statistical test supports both theories and fails to tell which one is right, which one is wrong. On the other hand, the great depths of certain banks given in this chapter and of certain reef-rimmed lagoons given in earlier chapters are seriously unfavorable to the Glacial-control theory but are perfectly consistent with the subsidence theory.

Banks in the West Indian Region

Many banks are charted in the West Indian region, of which only a few can be listed here. One of the best examples of a drowned atoll is Cay Sal in the Bahamas, south of Florida, HO 2145, 60 by 40 miles across, with a few small rim cays awash but with most of the rim 4 to 7 fathoms submerged. Several banks of large size lie southeast of the Bahamas,

HO 948: Caicos, 70 by 40 miles; Turks, 35 by 12 miles, 10 to 12 fathoms deep; Mouchoir, 31 by 10 miles, 12 to 13 fathoms deep; Silver, 33 by 35 miles, 15 to 20 fathoms; and Navidad, 24 by 11 miles, 15 to 20 fathoms deep. Their relation to former atolls is obscure; yet Agassiz noted that "the sunken banks of the Bahamas . . . remind us of the Great Chagos Bank" of the Indian Ocean (1894, p. 185). It is probable, however, that the Bahamas banks should be associated with the marginal belt of the Atlantic and hence that their depth may have been influenced by low-level abrasion, as has been suggested in Chapter XVI. Other banks, too numerous to be listed here, occur in the Caribbean Sea, of which a colored depth chart has been published by Agassiz (1894, Pl. 8). It is island-, reef-, and bank-free through its deep central area but contains many banks and reefs near its margins. The largest of these is Pedro Bank, north of Jamaica, HO 373, 96 by 56 miles, with reefs and cays only along the east half of the south side; its depth is hardly more than 20 fathoms. A smaller bank is Rosalind, next east of Yucatan Bank in the northwest Caribbean, HO 373. Whether the incomplete rims of these and other West Indian banks are all that remain of formerly complete, atoll-formed rims or are the precursors of future complete atoll rims cannot be determined in our ignorance of the history of the banks. Perhaps the existing relation of a partial rim on a bank elsewhere rimless has long obtained. It is interesting to recall in this connection that Darwin recognized the possibility that atoll reefs might grow up from steep-sided banks of small depth and that he thought "some such exist on the West Indies" (1842, p. 89). The banks above described may have given him this idea. In any case the abundant signs of instability on the islands and continental coasts of this region make it unreasonable to assume that the foundations of these banks have long been stable; yet the depths of the banks are fairly accordant. An inquiry concerning the controls of bank depths is therefore pertinent in this connection.

Limit of Bank Depth by Aggradation

The limitation of bank depth by the low-level abrasion of Preglacial islands and reefs does not seem to be applicable in the Caribbean Sea west of the Lesser Antilles. That region, like the great area of the coral seas in the Pacific, does not seem to give indication of such abrasional work in the form of cliffed islands, although in the Lesser Antilles cliffed islands are the rule. Hence other controls of bank depth must be sought for.

It has been suggested by Rein (1870) and by Murray (1880), as told in Chapter V, that stationary submarine banks might be aggraded by the accumulation of organic detritus and thus shoaled so much that reef-building corals could be established upon them and that atoll reefs would thus be built up to sea level. It may be further suggested that, if submarine banks, deeper than 40 fathoms, should subside at the same slow rate as that of their organic aggradation, their depth would remain

constant; also that, if they subside a little more slowly than the rate of their aggradation, their depth will be very slowly decreased; and that, if a slow decrease of depth be thus caused, it may be limited around the bank margin to about 40 fathoms. The reason is that, while the bank center could be built up somewhat more, the accumulation of fine detritus at smaller depths around the margin would be prevented by storm-wave action. This does not seem improbable in view of the fact noted on earlier pages that the exterior profile of coral reefs, especially the change from the gentle slope of the upper profile to the steep pitch below 40 fathoms, seems to be controlled by wave action with respect to present sea level. Hence the last of the above suggestions as to the limitation of bank depths involves only a somewhat different application of certain marine processes whose operation seems to be well assured. The occurrence of a considerable number of rimless banks in the coral seas with marginal depths of about 40 fathoms may thus find explanation. They may have had reef rims when originally submerged; but since then, what with the disintegration or burial of the rims and the aggradation of the lagoon floors, the whole surface of the bank may have gained a fairly even surface. If that surface were deeper than 40 fathoms when first formed by some submarine process independent of surface reefs, it may have been later shoaled to the limiting measure of shallowness at about 40 fathoms.

But, as already pointed out, it is strange, in view of the various indications of insular instability above brought forward, that a larger number of banks deeper than 80 or 100 fathoms are not known. It may be well believed that their absence from ocean charts does not truly mean their absence from the ocean itself. Navigators are generally satisfied of their safety when soundings of 50 or 100 fathoms do not touch bottom. The labor of making bottom soundings in the deep ocean with rope or wire is so great that vast areas of the Pacific, one or two of them about as large as Australia, remain to this day without a single authentic measure of bottom depth. Hence, although the future discovery of banks in the coral seas less than 50 fathoms deep is not probable, the discovery of banks 100 or 200 fathoms below the surface is eminently possible; particularly so in oceanic regions which, like those around Fiji and New Caledonia, appear to owe their present limits to a downwarping of a former greater extension. The account already given of the Stewart Bank in the China Sea warrants the hope that the newly devised apparatus for sounding by echo will in the near future settle the question here raised. This apparatus, once installed, can be used at short-time intervals very economically and without the delay of stopping the vessel that is required by line or wire soundings.

Summary

Nearly all the submarine banks at present known in the coral seas are of relatively small depth, generally less than 50 or 40 fathoms. But the

fact that a fair number of banks are known with depths of 60, 70, and 80 or more fathoms makes it clear that they at least cannot be the result of low-level abrasion acting on still-standing Preglacial islands. If they have rims they may be plausibly regarded as subsided atolls; and the foundations of such atolls cannot have been stationary. Among these deeper banks special mention may be made of those of Tutuila, Tonga, Fauro, Macclesfield, and Saya de Malha. The rarity of still deeper banks may be due, in part, to their aggradation by organic detritus after the cessation of an active subsidence by which a greater depth would otherwise have been caused. The occurrence of a good number of banks with marginal depths of about 40 fathoms gives some support to this view. But it is also possible that the absence of deeper banks may be more apparent than real; for the exploration of ocean depths, especially those of the Pacific, is as yet by no means completed.

The banks already known frequently occur in groups, as in Tonga, the Darwin Hermatopelago, the China Sea, the Coral Sea northeast of Australia, and the Chagos and the Nazareth hermatopelagos in the central and western Indian Ocean. They thus resemble atolls and elevated atolls, which are also often grouped together. For this, as well as for other reasons, banks may again be best explained as submerged atolls. The equable depth of reef rims in the Darwin Hermatopelago strongly suggests that their former limit of upgrowth was the sea surface and hence that they have been lately submerged. On the other hand, the unequal depths of the reef rims on the Palawan, Macclesfield, and Tutuila banks suggests an irregular upgrowth after an earlier subsidence. Most of these submarine structures are, however, not completely enough known to warrant confident statements about their origin. In particular the absence of living corals on certain bank rims of moderate depth calls for better explanation than has yet been given for it. Nevertheless the Grand Chagos bank, Darwin's type of a drowned atoll, is better explained as a drowned atoll than in any other way. The instability here inferred for many bank foundations makes the stability of the foundations of sea-level atolls highly improbable.

CHAPTER XVIII

THE FEATURES OF SEA-LEVEL ATOLLS

Outline of Inquiry

The explanation of sea-level atolls is the main problem of coral reef investigation. Taken by themselves they would remain mysterious. It is for this reason that all other kinds of reefs have been studied in earlier chapters of this volume, before here devoting a next-to-final chapter to these inscrutable structures. Fortunately, the evidence presented in the earlier chapters as to the origin of certain barrier reefs at sea level, above sea level, and below sea level, as well as to the origin of certain elevated and submerged atolls, bears helpfully on the origin of atolls at sea level. For, if those other reefs have been formed by upgrowth on subsiding foundations, then sea-level atolls also have probably been formed in that way. But for the present these various lines of indirect evidence as to atoll origins will be set aside, and the effort will be made to learn, if possible, something of their origin from sea-level atolls themselves. It will thus be told that certain intensive studies of individual atolls have yielded results of interest even if they are not universally regarded as having demonstrated atoll origins. It will also be shown that the location of a good number of sea-level atolls near certain barrier-reef islands, which occupy demonstrably unstable areas, strongly suggests that instability characterizes the area of the near-by atolls also. Finally, it will be pointed-out that the highly peculiar features of the Maldive atolls, southwest of India, which may be well regarded as the most extraordinary group of atoll reefs in all the oceans, are better explained by Darwin's theory of upgrowing reefs on subsiding foundations than by any other. But, before these systematic sections are entered upon, a more general paragraph will be inserted.

Some General Notes on Atolls

One of the earliest accounts of an atoll is found in the Voyage of François Pyrard de Laval to the East Indies, as translated and published in "Purchas His Pilgrimes." That voyager, having been wrecked on one of the Maldives, described it as follows: "Every Atollon is seperated from others, and contaynes in it selfe a great multitude of small Iles; It is admirable to behold, how that each of these Atollons are invironed round with a huge ledge of Rockes . . . Being in the middest of an Atollon, you shall see about you a great ledge of Rockes which impale and defend the Iles, against the impetuousnesse of the Sea. But it is a very fearefull thing even to the most couragious to approach to this ledge, and see the waves come afarre off and breake furiously on every side.

For I assure you, as a thing which I have seene a thousand times, that the surge or billow is greater then a House, and as white as Cotton: so that you shall view round about you as it were a very white Wall, especially when the Sea is loftie" (Glasgow edit., 1905–1907, Vol. 9, p. 508). It is natural that the attention of this early observer was attracted by the most visible features of the atolls he visited and that he made no inquiry whatever as to their origin. It was not until over a century later that speculation, little trammeled by geological principles, arose as to how atoll reefs are built and how they acquire their peculiar ring-like form. It was then that the idea of their being based on the rims of submerged volcanic craters had its birth. The arguments by which Darwin disposed of that idea have already been outlined in Chapter II of this volume.

The largest atolls of all the coral seas are Kwajalong or Menschikov in the Marshall group, 65 by 10 or 15 miles; Namonuito in the Caroline group, 40 by 30 miles; and Ari, one of the Maldives, 48 by 18 miles. The drowned Chagos Atoll is larger than any of these, as its diameters are 95 and 75 miles. Cay Sal in the Bahamas, apparently a drowned atoll, is 60 by 40 miles across. If the low limestone islands of the Bahamas represent former atolls, a little elevated and slightly modified by low-level abrasion, the largest of them would have perhaps rivaled a similar former condition of the now depressed Seychelles bank in the Indian Ocean, which with its dimensions of 200 by 80 miles would have far exceeded the size of any existing atoll.

Most atolls depart rather freely from the ideal oval or circular outline in which they have often been figured. Nevertheless it is reasonably expectable that an atoll of whatever original pattern should be reduced to a smaller and more nearly circular outline if its upgrowth is long continued. For its salient angles, on the talus beneath which the reef detritus must be thinly distributed over a broadening downslope, may for a time be sharpened by upgrowth, but they will thereafter retreat in blunted form as the reef grows higher; while the reëntrants will for opposite reasons be somewhat filled out. An apparent confirmation of this view is found in the relatively simple outline of most small atolls, in contrast to the much more irregular outline of many large atolls. Unusually symmetrical forms are exhibited by the Minerva atolls, west of Tonga, HO 2018 (Fig. 222): North Minerva is a nearly circular reef, 4 by 3 miles across; South Minerva is a doublet or figure-8 atoll, each member being 2 miles in diameter.

The Smallest Atolls as Witnesses for Darwin's Theory

One of the smallest lagoon-enclosing atolls is Momo or Horseshoe reef, HO 2859, about a mile in diameter, between Wakaya and Mbatiki in central Fiji. The lagoons in atolls of small size are usually filled up. A number of small, lagoonless reefs, some being slightly elevated, occur in

or near the Phoenix group, next to the vast blank space of the Pacific that spreads thence northeast to Hawaii. Inasmuch as minute atolls appear to be, according to Darwin's theory, on the verge of extinction by tapering upgrowth during slow submergence, that blank space has often been inferred to contain a number of already extinguished atolls; if so, they may be found by echo sounding. Other examples of minute atolls are: Triton, HO 2785, a mile in diameter, in the China Sea; Nanomana, HO 1981, in the Ellice group; Vostok and Nassau, both on HO 1980, the first being a third of a mile in diameter in latitude 10° S, longitude 152° W, and the second half a mile in diameter in latitude 11½° S, longitude 165½° W; and Awiu and Liot, near Ninigo, north of New Guinea, each a mile in diameter. In the Banks group, Anuda or Cherry Island, HO 1984, may soon become a small atoll; it is now ½ by ¼ mile across, 212 feet high, with a narrow fringing reef.

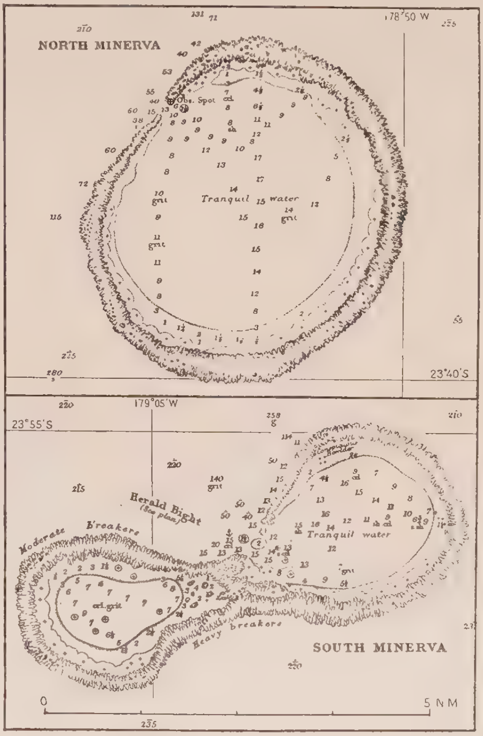


FIG. 222—North and South Minerva Atolls; HO 2018.

The charts show also a considerable number of minute reefs awash, which are presumably on the verge of extinction by subsidence. These reefs furnish an interesting argument for Darwin's theory. If they have been formed on stationary foundations, their volcanic undermasses must have been peaked volcanic summits, recently built up a little under or a little over sea level. For, if the cones had been built up well above sea level, the reefs would not be so small as they are after the cones had been worn down to dissappearance; and, if the cones had been built up close to sea level a considerable time ago, the reefs would now have gained a significant diameter by outward growth, like Christmas Atoll. Hence, instead of so many cones recently conspiring to grow up close to sea level, it seems more probable that many volcanic cones, the summits of which rose at various dates to moderate heights above sea level, supported reefs of small circuit which were reduced to a minute or vanishing size by inward upgrowth as the cones sank beneath the waves. This inference in favor of Darwin's theory is one of the few that is reached

through the study of sea-level reefs alone. If it could be said of natural law as it is of civil law: "De minimis non curat lex," no attention would be paid to an inference based on these apparently insignificant little oceanic structures; but, as a matter of fact, natural law is as much concerned with little things as with great things. It would be as unreasonable to suppose that all the many minute reefs of the Pacific were based on still-standing volcanic cones, the summits of which rose nearly to or a little

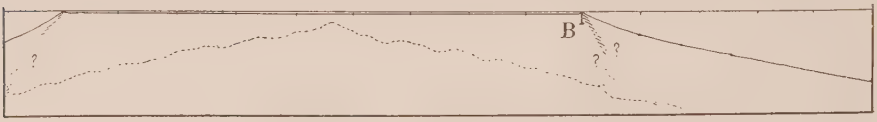


FIG. 223—Cross section of Funafuti Atoll, showing depth of boring in its reef.

above the ocean surface, as to suppose that all the atolls of the great ocean were based on still-standing crater rims that conspired to approach but not to attain the surface of the sea.

Funafuti and Its Deep Boring

Two Pacific atolls have been penetratingly studied. The more famous of these is Funafuti, in the Ellice group, HO 127, 13 by 11 miles, with a narrow reef and a lagoon 20 or 30 fathoms deep. Here a boring 1114 feet deep, *B*, Figure 223, was made under the direction of a committee of the Royal Society of London. The depth reached was a very small fraction of the probable total thickness of the atoll structure according to Darwin's theory. Unfortunately the boring was made on the atoll reef where the supposed volcanic foundation is deepest, instead of on a shoal near the lagoon center, below which the foundation probably lies nearer the sea surface; and again, unfortunately, the experts who afterwards made special examination of the core of the boring were, according to Skeats (1918), instructed by the Royal Society committee to report only on facts, not on theories. Thus those best qualified to express opinions on the main question at issue—namely, the inferred processes of the past which would most competently explain the observed facts of the present—were not given opportunity to do so officially.

The chief account of Funafuti is given in the Royal Society's report (1904), from which a brief extract has been made in Chapter I; other and shorter accounts of the atoll have been published by Sollas (1899), Mrs. David (1899), Hedley (1896), Gardiner (1898), and Agassiz (1903a). Perhaps the most significant result gained from the boring was that the fossils found in the core were characteristic of shallow water only; while living organisms dredged from the external slope of the atoll at depths similar to those reached by the boring were in part such as lived at those depths and in part such as, living at lesser depths, sank to deeper water when dead.

It may be here noted that elevated atolls, as in the Kambara belt, Fiji, and the Loyalty Islands, offer a much more convenient field for the investigation of atoll structure by boring than any sea-level atoll can, because borings may there be made at the center of the former lagoon as well as at any distance from the center on any outgoing radius.

The Value of Gravity on Jaluit Atoll

Jaluit atoll, in the Marshall group of the North Pacific, HO 1749, 20 by 32 miles, with a lagoon 25 to 30 fathoms deep, may be recalled as having led Schnee (1904) to become a strong supporter of Darwin's theory; thus balancing the opposite opinion reached by Wood-Jones on Keeling Atoll and supporting my contention that, if an atoll is studied alone, one may hold any theory of atoll formation that he likes. Jaluit has recently been the site of one of the most remarkably penetrating studies made in any ocean; namely a determination of the local value of gravity made by Matsuyama (1918), with the aid of an Eötvös gravity varimeter. He found that the observed value of gravity at sea level on Jaluit atoll will best agree with the expectable value of gravity for a mid-ocean, sea-level station, if a considerable part of the submarine mass below the atoll is assumed to consist of limestone with a specific gravity a little less than 2.00, and not of basalt with a specific gravity of 3.00 or more. The thickness of the limestone capping on a volcanic foundation that gives the best agreement between observed and expected gravity values was between 243 and 1000 meters.

This investigation deserves to be regarded as one of the most delicate and impartial that has yet been made on atoll structures. Its result contradicts several theories, namely those of Murray, Wharton, Agassiz, and Daly, in so far as they assume the existence of truncated volcanic foundations at a small depth beneath atoll reefs. On the other hand it matches a deducible consequence of Darwin's theory, to which reference was made, without specifying it, in the first paragraph of Chapter III; and it thus gives support to that theory. But it gives similar support to the Rein-Murray theory of organic aggradation of stable submarine banks—presumably volcanic cones—until they are shoaled sufficiently to serve as foundations for reef upgrowth. Hence choice between these two supported theories must be looked for elsewhere: for example, in the uplifted atolls and almost-atolls of eastern Fiji, where the Rein-Murray theory is excluded and the Darwin theory is confirmed in a most convincing manner.

Two other Japanese observers, Yabe and Aoki (1922), have found, also on Jaluit atoll, a fragment of a conglomerate in which a pebble of limestone contained fossils which they interpret as of mid-Tertiary age; and from this they infer that a limestone mass of that age forms the core of the atoll. Whether the present fauna of the surrounding sea is well

enough known to demonstrate the mid-Tertiary age of the fossils is perhaps, in view of doubts of a similar nature that I have raised in connection with the elevated reefs of Mangaia and Uvea, an open question. But in any case the bearing of this discovery upon the history of the atoll cannot be safely determined until the source of the conglomerate is found.

In the meantime it may be suggested that, if the pebble fossils are truly of mid-Tertiary date, the limestone from which the pebble was derived was presumably a part of an earlier atoll which not long ago, either by reason of long continued stability or of recent upheaval, was accessible to modern erosional or abrasional processes at normal ocean level. If so, the earlier atoll cannot have been treated as it should have been under the Glacial-control theory. For under that theory, it should have been, during a long period of nearly perfect stability, cut down to a platform by low-level abrasion in the Glacial period and afterward covered by a Postglacial reef and its lagoon deposits. Under these conditions no fragments of the mid-Tertiary reef should be discoverable in the sea-level atoll of today.

The Vegetation of Rose Atoll, Samoa

Rose Atoll, the easternmost member of the Samoan group, HO 2924, about 3 miles in diameter, deserves mention because, as Dana pointed out (1885, p. 100), it is the last term of a sequence which begins with the active volcanic island of Savaii at the western end of the group. The Samoan Islands thus repeat, but in a less complete manner, the sequence that begins with the young cone of Mehetia, the easternmost member of the Society Islands, and ends with several atolls far to the northwest. But Rose Atoll also deserves mention because of the careful account of the vegetation on its reef islets and on the reef itself given by Setchell (1924). As on other atolls, the vegetation of reef islets does not seem to consist of the survivors of a flora that presumably once existed on a now vanished, central volcanic island; it consists of newcomers, waifs of chance arrival. As Darwin long ago said of Keeling Atoll in the Indian Ocean, it "has quite the character of a refuge for the destitute" (1840, p. 541) in so far as its land plants are concerned.

But in addition to the reef-islet land plants, Setchell emphasizes the great importance of the lime-secreting, reef-building nullipores, especially Lithothamnium, on this atoll: "The Porolithon association may be looked upon as the reef-builder." This Lithothamnium "is closely adherent to its base of attachment by a broad, tightly adhering crustaceous and stony layer. From this base arise thick, branching, cylindrical or slightly compressed and closely arranged erect portions, forming rosettes of greater or less diameters. These resist the onslaught of the waves through their rigid and stony consistency. . . . The atoll-rim is a solid white limestone and consists of little else than this Porolithon. . . .

The entire reef is made up of a single species" (1924, pp. 242, 243). Yet, closely as the existing organisms of the reef surface are studied in their present relations, how impossible it is to infer from them the various changes that have taken place since the presumable initial volcanic cone was built up by eruption, although many of these changes must be recorded in the invisible subsurface structures of every atoll in the Pacific.

Other Pacific Atolls

Several atolls near the margin of the Pacific coral seas may be noted. One is Wakes Island, HO 162, 4 by 2 miles, without near-by soundings; it is in latitude 19° N, longitude 166° E, and is the northernmost atoll in the Pacific coral seas. The southernmost atolls are in latitude 24° S: they are Ducie, HO 1977, 1 by 2 miles, longitude 125° W, and Oeno, HO 1977, 2 miles in diameter, longitude 131° W, with a half-mile reef flat and a shallow lagoon. Little Clipperton Atoll and its small Rock, HO 1680, may be once more mentioned here; it is the easternmost atoll in the Pacific, standing in latitude 10° N, longitude 109° W, in a vast island- and reef-free space of open ocean. An atoll of simple form is Caroline, not a member of the Caroline group, but standing alone north of the Society Islands, latitude 10° N, longitude 150° W, HO 928; it has been described by Holden (1883), who visited it to observe a solar eclipse. Various other atolls might also be noted, for accounts of many have been read over. Their size and form vary; their reefs and lagoons are in general much alike; but they agree best in silence as to their origin.

Atolls in Unstable Regions

Lagoon Atolls

Lagoon atolls have been defined as atolls which rise from the floors of lagoons enclosed by barrier reefs. They are not numerous, but they have significance, first, in that their formation must have been conditioned by the same changes of level as those which controlled the development of the near-by barrier reefs, and second, in that their close resemblance to open-sea atolls in all particulars except the small depth of the waters around them permits the application to open-sea atolls of whatever explanation is found for lagoon atolls.

Thus the two lagoon atolls, Thakau Levu and Ovatoa, each about 5 by 3 miles across, not far from the west end of Vanua Levu, Fiji, stand in the lagoon, HO 2856, enclosed by the great barrier-reef loop that extends far west of that large island. Hence they must have experienced changes of level similar to those of the island end near which they stand and similar also to those suffered by the well embayed island of Yendua, HO 2856, which rises a little west of the atolls from the same broad lagoon floor. If these lagoon atolls owe their formation to upgrowth during the sub-

sidence of their foundation, then the larger, open-sea atolls, Vatu-i-ra and Charybdis, which rise from the deep-water passage, HO 2856, between Vanua Levu and Viti Levu to the southwest, have probably also been formed by subsidence-compensating upgrowth; and yet their lagoons have ordinary depths. Agassiz stated, subsidence being implicitly excluded, that these two open-sea atolls "represent probably the eroded summits of a more or less circular island and of an elongated ridge, on the outer edges of which coral patches have found a footing" (1899, p. 127); but as an origin for atolls without subsidence is contradicted by all that is learned from elevated reefs in Fiji, it cannot be accepted. A few lagoon atolls of smaller size occur in the imperfectly enclosed, barrier-reef lagoon, HO 2857, northwest of Viti Levu. The clear evidence for the instability of this district as given by the deepening of the lagoon to the northwest and the gradual submergence of its western reef has been presented in the account of the Fiji barrier reefs.

Lagoon atolls also occur sparingly in the broad southwestern lagoon of New Caledonia and in the still broader lagoon of the Great Barrier Reef of Australia, for both of which instability seems demonstrated by the geological history and the physiographical development of the reef-fronted coasts. Several lagoon atolls rise from the Tonga banks, as described in Chapter XVII. As to the atoll-like reefs in the Australian lagoon, Hedley and Taylor seem to be right in ascribing the pattern of certain horseshoe "cays" in those shallow waters largely to wind and wave work (1907, p. 407). The depth from which the cay-shaping spits of drifted coral sands are there built up is not nearly so great as it would be in the case of mid-ocean atolls, which Wood-Jones (1910) explains by the same process, as further told below.

Small Atolls Near Large Barrier-Reef Islands

As atolls taken alone are so uncommunicative, we are driven to seek information about them from their more communicative neighbors. Just as the origin of the lagoon atolls mentioned in the foregoing section may be inferred from changes of level suffered by the neighboring, reef-encircled, high islands, so the origin of deep-water atolls which stand outside of but near barrier reefs may be inferred from the origin of the barrier reefs, which is in turn inferred from the changes suffered by the islands encircled by the barrier reefs. An example of this sort of vicarious investigation has already been given in the application of the testimony secured from the elevated limestones of the Exploring Isles in eastern Fiji to the explanation of several little deep-water, sea-level atolls that stand near by.

Similarly, whatever explanation is finally adopted for the barrier reef of Ngau (Fig. 159), in central Fiji, must apply to the little Mambulitha atoll 5 miles to the south; and the same relation will presumably hold between Nairai, also in central Fiji, and the little circular atoll, Momo or Horseshoe,

10 miles to the northwest in the direction of the evidently tilted lava-bed mass of Wakaya. This relation will again obtain between the tilted atoll of Vatu Leile (Fig. 213), in southwestern Fiji, and the minute Lakaleka reef 8 miles to the east; and between several of the reef-encircled limestone islands of the Ongea belt in eastern Fiji and the small atolls near them, as shown in Figure 208. It is noteworthy that in all these examples the atoll is smaller than the barrier reef near which it stands; and that is natural enough, because on almost any theory of reef origins a small island will be replaced by an atoll sooner than a large island will be.

A statistical statement for Fiji atolls may be here introduced. The large-scale charts of the group show 44 atolls, large and small, including certain minute reefs without central lagoons; also 3 almost-atolls with volcanic islets; and 10 almost-atolls with limestone islets. Of the 44 atolls the largest is Ringold, near the northeastern margin of the archipelago, a rambling structure of wave-washed reefs, over 30 miles long, north-south, by from 4 to 7 across. In view of the abundant evidence for the instability of various Fiji islands of decipherable history, it is impossible to believe that the many atolls of the group crown shallow, truncated platforms abraded on long stable, greatly worn-down and deeply weathered volcanic islands, as demanded by the Glacial-control theory. And yet the Fiji atolls have been instanced as having stable foundations.

Several atolls that stand in a systematic relation to the volcanic members of the Society Islands have been specified in the account of that group. Similarly the description of the barrier reefs of the Caroline Islands made mention of Andema atoll, standing 10 miles southwest of the barrier reef of Ponape. Again, between the reef-encircled volcanic islands of Kusaie and Ponape in the same group, is the atoll of Pingelap, HO 1756, 1 by 2 miles across, with a lagoon from 16 to 38 fathoms deep; its foundation has probably suffered about the same subsidence as that indicated by the embayed valleys of its volcanic neighbors. Royalist atoll, 12 by 5 miles, with one lagoon sounding of 14 fathoms, lies next south of the almost-atoll of Truk in the western Carolines, the surviving, mountain-top islets within which, as well as its lagoon depth of 58 fathoms, are strongly suggestive of subsidence. Three small atolls north of the Pelew Islands have been noted, in the account of that group, as suggestive of a very gentle northward tilting. Northwest of New Caledonia, 100 miles, and 20 miles beyond the end of its great barrier reefs, are the D'Entrecasteaux atolls, HO 2027, 20 and 15 miles in diameter, without charted soundings. About 8 miles northwest of the reefs that mark the down-tilted side of Uvea, the westernmost of the Loyalty Islands, is Eo or Beautemps-Beaupré atoll, 7 miles across, with a single lagoon sounding of 12 fathoms.

Atolls in the Unstable New Guinea Region

The accounts of the Solomon Islands given in earlier chapters suffice to show that they long have been and still are actively unstable. Only one

atoll lies near them; it is Rua Sura, 4 miles northeast of Guadalcanar, 3 by 1½ miles, with the unusual depths of from 30 to 49 fathoms in its small lagoon. Other atolls of larger size occur at greater distances from this group. Ongtong Java or Lord Howe Atoll—not to be confounded with the volcanic and high-cliffed Lord Howe Island in the marginal belt between New Zealand and Australia—about 150 miles northeast of the Solomons, HO 2910, measures 30 by from 7 to 15 miles; it has a reef flat a mile

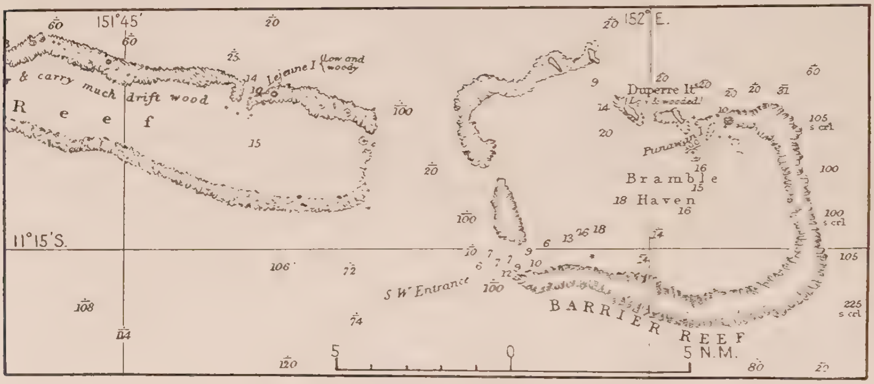


FIG. 224—Long and Bramble Haven Atolls, east of New Guinea; HO 2950.

wide and a lagoon, imperfectly sounded, with 21 fathoms as its greatest depth. A brief general account of this atoll has been given by Woodford (1909). Nukumanu or Tasman atoll, about 40 miles north of Ongtong Java, HO 2899, 10 by 7 miles, has a reef flat half a mile to a mile wide and a lagoon from 17 to 20 fathoms deep. Roncador or Candelaria, BA 214, 6 miles in diameter, stands between Ongtong Java and the island of Isabel in the Solomons. Kilinailau or Carteret atoll, BA 214, is 50 miles north of the northwest end of the Solomon group; it is 13 miles in diameter and has a lagoon from 20 to 22 fathoms deep. Between Kilinailau and Ongtong Java is Marqueen or Mortlock atoll, BA 214, 8 miles in diameter. The three Indispensable atolls lie south of the eastern Solomons and 40 miles beyond the raised Rennell atoll; they are 12 by 4, 22 by 17, and 13 by 5 miles; no soundings are shown in their lagoons. Although these atolls are not close to the Solomons, it would be hazardous, in view of the active instability of those islands, to conclude that the atolls stand over a long stable area of the ocean floor.

The pronounced instability of the entire New Guinea region, including the Solomon Islands on the southeast and the Louisiade Archipelago on the east and many large islands to the north, is not to be questioned. In view of the continuation of the deformed mountain-range structures from New Guinea through the Louisiade Islands, the occurrence of Pocklington atoll, 18 by 3 miles, 100 miles farther east, is of special significance. It is highly probable that submerged islands and reefs may be discovered in the intermediate unsounded space. Moreover, between

the tilted reef of Panniet Island and the west end of the great Tagula barrier reef are two small atolls: one is 5 by 2 or 3 miles across, with a lagoon 10 fathoms deep; the other is a mile in diameter: again, between the Louisiades and easternmost New Guinea are three good-sized atolls with normal lagoon depths, all on HO 2950: Bramble Haven (Fig. 224), 6

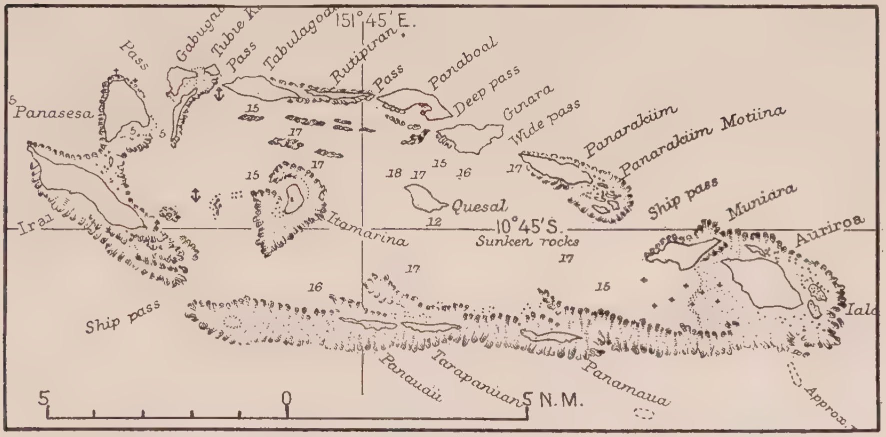


FIG. 225—Conflict Atoll, east of New Guinea; HO 2950.

by 9 miles, with a mile-wide reef flat and lagoon depths of 16 to 20 fathoms; Long, partly shown in the same figure, with discontinuous reefs, 20 by from 3 to 6 miles, and one lagoon sounding of 15 fathoms; and to the north, Conflict (Fig. 225), 17 by 5 miles, with discontinuous reef patches up to a mile in width and ordinary lagoon depths down to 18 fathoms. These three examples seem to be of critical value. North of the Louisiades and not far from Woodlark Island, which bears elevated reefs, is Nada or Laughlan atoll, HO 2942, with an imperfect reef, 6 miles across and no lagoon soundings. North of Geelwink Bay, in northwestern New Guinea, is Mapia, HO 3003, 10 by 16 miles; and 150 miles west-northwest of Admiralty Island is Ninigo, HO 2969, 15 by 18 miles, with a mile-wide barrier reef flat and lagoon depths down to the large measures of 52 and 55 fathoms. Several small atolls are not far away: to the northeast are Pellelulu and Heina, 5 and 2 miles across, with lagoons 11 fathoms deep; 5 and 8 miles to the southwest are Suma, 2 miles, and Sumasuma, 3 by 2 miles; Liot and Awiu, both a mile across, are farther south.

Atolls in the Dutch East Indies

The occurrence of atolls in the East Indies has been a subject of controversy between Wichmann (1912) and Niermeyer (1912), whose views based on incomplete surveys and on still more incomplete discussion do not well represent the present aspect to the coral reef problem. Wichmann even doubted whether atolls can be formed in the archipelago because it has experienced "an extensive upheaval"; he thus failed to

recognize the extreme diversity of its recent warpings. Niermeyer took no sufficient account of possible rapid subsidence and the resultant imperfection of reef upgrowth; he concluded that several discontinuous reefs along the margin of island-bordering shelves, as along the northeast arm of Celebes, are witnesses against Darwin's theory. A much better discussion is given by Molengraaff (1922, pp. 309–337), who presents several detailed maps of atolls which rise from the deep-water and unstable region between Borneo and Celebes on the north and Sumbawa on the south, east of the stable and shallow Sunda Sea. These atolls have imperfect reef rims and broad reef patches in the lagoons; they might therefore be regarded as patches of reef rising from banks, instead of as typical atolls. But they may be still better regarded as atolls that had formerly reached a mature stage of lagoon filling and that have since then suffered so seriously from low-level degradation during the Glacial period that they are not yet fully restored to good condition. In view of their imperfect reef rims they have perhaps suffered also a slight subsidence during the Postglacial rise of ocean level.

The largest examples given by Molengraaff are: Kalukalukuang, Dutch HO 128, 60 by 35 miles, with reefs and shoals in the northeastern part of the imperfectly enclosed lagoon and increasing depths to the southwest down to 99 fathoms. Near by on the southeast are the three Laars banks, 13, 10, and 20 miles long; the northeastern end of the northeastern bank has a reef rim, elsewhere these banks are almost rimless. The four following are on Dutch chart 374: Postillion, 50 by 32 miles, with many small reef islands around its eastern side but none on the west side, where depths of 16 fathoms prevail while depths of 37 fathoms are charted in the central area; Sapuka, 23 by 18 miles, with small reef islands all around the rim and with lagoon depths increasing to 43 fathoms on the south side; Paternoster, 53 by 9 miles, with a discontinuous rim of reefs or shoals and an interior depth of from 30 to 39 fathoms; Zandbuis, 10 by 5 miles.

Molengraaff is inclined to regard the floors of these atolls as platforms abraded by the low-level or rising ocean of the Glacial epochs (1921), and he takes little account of their Postglacial aggradation. But in view of various facts concerning the coral seas presented in the present volume it is difficult to believe either that coral growth was sufficiently weakened in this region during the Glacial epochs to permit abrasion or that Postglacial aggradation is negligible. It seems, on the other hand, eminently possible that, as above suggested, the predecessors of these atoll reefs and reef flats were exposed not to abrasion but only to low-level degradation by rain-water solution during the latest Glacial epoch at least; that the present reefs have grown up from the reef surfaces then emerged and worn down; and that during their upgrowth they furnished detritus with which the present banks are more or less aggraded. Thus interpreted, the present submergence of the worn-down atolls may be due not only

to Postglacial ocean rise but also in part to recent and unequal subsidence, especially where marked inequalities of lagoons depths are charted, as in Kalukalukuang. In any case it seems permissible to regard these atolls as not belonging in the western stable area of the shallow Sunda Sea but in an unstable eastern area which is characterized by islands bearing unconformable elevated reefs and by deep mediterranean seas.

There can be little question that such is the case with several atolls which are found, to the east of those above named, in the deep Flores Sea south of Celebes and which Molengraaff supposes to have been built up from subsiding foundations. The largest of these is Tiger atoll, Dutch chart 372; it measures 40 by 20 miles and has an imperfect reef rim; many reef flats rise from the lagoon floor where depths of 30 and 40 fathoms occur. As the flats are alternately submerged and emerged with the rise and fall of the tides, the change of appearance of the lagoon thus caused is said to be astonishing. Near by to the northeast is a smaller but better-defined atoll, 6 miles in diameter with lagoon depths of 14 fathoms. Southwest of Tiger atoll, 15 miles, is the mountainous island of Tana Jampea, already described as surrounded by a submerged barrier reef. Farther north and nearer Celebes are the Tukang Besi Islands, Dutch chart 317, in which two belts of sea-level atolls alternate with two others of elevated atolls, as already described in the chapter on elevated reefs. It is significant that the sea-level members of this evidently unstable group have normal lagoon depths.

Atolls in the Deep China Sea

The manifest indications of strong and recent subsidence along the reefless southern coast of China and the many proofs of instability in the Philippine Islands have already been adduced as suggesting that the deep floor of the intermediate China Sea must also be unstable. This suggestion receives support from the considerable depths of the Macclesfield and other banks in that sea and also from the decidedly greater depth of the newly discovered Stewart Bank, as has been told in the preceding chapter. It is therefore of interest to find that a normal atoll stands farther north in the same sea: it is Pratas Reef, about 140 miles southeast of Hongkong, HO 2784, of nearly circular outline, 12 miles in diameter, but breached on the southwest. The reef flat is from half a mile to 2 miles wide, and the lagoon has the very moderate depth of 10 fathoms. Other atolls hereabouts have been noted in the account of the banks of the China Sea.

The Atolls of the Indian Ocean

The Keeling Atolls

If exception be made of the Maldive and Laccadive Atolls not far from the west coast of India, it may be said that the Indian Ocean is character-

ized rather by drowned atolls and banks than by sea-level atolls. It may be added that most of the not numerous atolls are in the western part of the ocean and are of imperfect form. Two Indian Ocean atolls, however, lie only 15 miles apart far to the east and are of good development: they are Keeling and North Keeling Atolls, HO 3109, 6 by 9 and 1 by 2 miles across. The first is famous as the only atoll that Darwin had opportunity of studying; some of his comments upon it have been quoted in Chapter I. It has been later examined by Forbes (1879), Guppy (1889a), and more in detail by Wood-Jones (1910). The reef has a broad flat on the south but is breached on the north; the lagoon is only from 4 to 8 fathoms deep. Guppy's estimate of the amount of reef detritus annually swept into the lagoon has been given in our first chapter. Present-day processes may be well studied here, but the past history of this atoll is as inscrutable as that of its Pacific homologues. In spite of all the attention that has been given to it, no means of demonstrating any proposed explanation of atoll origins have been found in its visible structure.

Wood-Jones, a physician resident on Keeling Atoll for several years, apparently unacquainted with other coral reefs and therefore without compelling reasons for the acceptance of any theory of reef formation, adopted a theory that satisfied him best—a theory of reef growth on a stable foundation—and thus became a persuaded opponent of Darwin's theory. Yet it should be apparent that a well supported explanation for this atoll, or for any other, can be best found in other parts of the coral seas, where barrier-reef islands and elevated reefs offer fuller evidence of reef origins. The same observer gained from the study of Keeling Atoll what seems to me an exaggerated measure of the influence of wind-driven waves in shaping reef patterns; thus reviving a suggestion long before made by Semper. For if such influence were generally more dominant than that of the now submerged shore line from which, as it may be believed, atoll reefs grew up, the pattern of atolls ought to be more uniform than it is.

This principle is more clearly illustrated by the pattern of barrier reefs, within which a high island still survives, than by the pattern of atolls. It is true that certain barrier reefs lie close to or even fringe the windward side of their islands and loop out from the leeward side, as in the case of the south-central Fiji island of Ngau (Fig. 159). Yet the barrier reefs of numerous other islands are separated from their central islands by a lagoon of fairly even width on all sides, as in the case of another south-central Fiji island, Totoya (Fig. 155). And in still other cases, like that of Lakemba in eastern Fiji, the reef fringes the leeward side of the island and loops several miles off shore as a barrier on the windward side. Kanathea (Fig. 201), as another east-central Fiji example, has its barrier-reef loop extending several miles across the direction of the prevailing winds. The great barrier reef of Tagula in the Louisiade Archipelago is a striking case of asymmetrical reef growth; it fringes the island for a little

distance along its northeast shore and loops many miles away from it to the east, south, and west. The near-by island of Rossel has east-and-west reef loops. In all these cases the fringing-reef form of the shore line from which the barrier reef has grown up, taken with the slope of the subsiding coast, appears to have been much more determinative of the present reef pattern than the wind direction has been. The same rule presumably holds for atolls.

Diego Garcia, Near the Drowned Chagos Atoll

The atoll of Diego Garcia, near the center of the Indian Ocean and about 50 miles south of the drowned atoll of the Chagos bank, BA 920, measures 12 by 3½ miles across and has a reef flat a mile or less in width with a lagoon 14 fathoms deep. It has been studied by Bourne (1888), who argued well in rejecting the possibility of lagoon excavation by solution, because of the large quantity of inwashed and locally supplied detritus by which the lagoon floor is continually aggraded. But the views adopted by him regarding the origin of the atoll seem to me untenable; for he looked favorably on the idea that Diego Garcia is, in accordance with Wharton's hypothesis, underlain by a platform of normal abrasion, although he gave no reason for the absence of defending reefs while abrasion was in progress or for the absence of cliffs on barrier-reef islands elsewhere, though such cliffs certainly ought to occur if atolls have abraded foundations. Just as for Keeling Atoll, so for Diego Garcia the true explanation must be sought elsewhere.

Several unimportant atolls occur north of Madagascar, in association with the banks of that region.

The Maldive and Laccadive Atolls

The Maldive atolls, BA 66 a, b, c, in that part of the Indian Ocean southwest of peninsular India known as the Arabian Sea, consists of some 20 well defined members, from 10 to 48 miles in longer diameter and up to 17 miles in shorter diameter. They form a chain 470 miles in north-south length. Through its middle part the chain consists of two sub-parallel ranges of atolls, from 10 to 25 miles apart; the intervening waters have a depth of from 200 to 500 fathoms. The larger individual atolls are peculiar in having their reefs greatly subdivided, and some of the patches are further peculiar in being ring-shaped. These rings resemble small atolls and are called faroes. The Pacific affords only one incomplete example of this kind: that of the western half of the great Tagula barrier in the Louisiade Archipelago, to which further reference is made below. The Maldive lagoons usually contain many additional reef patches; thus Ari atoll, 48 by 17 miles, the largest member of the group, has 50 or more reef patches or faroes in its reef ring and over 70 patches in its lagoon. The depth of the Maldive lagoons increases southward, from about 20 fathoms

in the northern atolls to 46 fathoms in the southern; this is further considered below.

To the north are the Laccadives, BA 827, including a dozen scattered atolls and banks, mostly of small size. Between the Maldives and Laccadives is the isolated reef of Minicoy, BA 827, 7 by 3 miles, which has been described by Basevi (1872). The following discussion concerns the Maldives, as they have been more closely studied than the Laccadives.

Agassiz, Gardiner, and Daly on the Maldives

The Maldives have been well described as to facts of occurrence by Agassiz (1903b) and Gardiner (1902, 1903, 1903–06); but in the discussion of reef origin neither of these experienced observers has given sufficient consideration to various alternative theories which compete with the theories adopted by them, nor have they deduced and defined the peculiar consequences of their adopted theories in such a way as to test them adequately. Agassiz states that "the composite atolls of the Maldives have arisen upon minor elevations upon the greater Maldive plateau which have given to the reef-building corals a base at the proper depth from which they have risen to the surface" (1903b, p. xx). No sufficient explanation is given for the origin of the plateau or of the minor elevations that are supposed to stand at a proper depth for coral growth; and no account is taken of the possible occurrence of subsidence during the formation of this remarkable chain of reefs.

On the other hand, Gardiner, while recognizing that the depression of a large land area between India and Madagascar took place in Tertiary time, arbitrarily decides that "this depression is not the same as the slow and long-continued subsidence, postulated by the upholders of the Darwinian theory" (1903, p. 205). In one sense this decision is probably true; for, if it were not, every large eminence of the sunken land ought to be represented today by an atoll. But in another sense it does not seem to be true, for a number of more or less imperfect atolls do occur in the region of the sunken land; witness the several atolls that rise from the great Seychelles bank and the many reefs and banks which constitute what I have above called the Nazareth Hermatopelago on the great sea-floor swell northeast of Madagascar. It is to be presumed that those reefs, as well as the banks associated with them, mark summits of that part of the sunken land which did not, during the later stages of sinking at least, subside fast enough—except recently, when the atolls were submerged into banks—to drown the reefs that had grown up over them. The case is analogous to that of the less extensive area of lost land between northeastern Australia, New Guinea, and New Caledonia, the subsidence of which appears to have been accompanied by the upgrowth of so many atolls—except in the central area where the depth is over 1000 fathoms—that the region is known as the Coral Sea. Taking no explicit account of this, and "seeing the absolute impossibility of subsidence affording any explanation" for

the Maldive reefs, Gardiner concludes that "an almost flat plateau at a depth of 140 to 170 fathoms was at one time formed by the erosion and denudation of an original land mass or more probably series of masses" and that the present shoals and reefs were afterwards built up upon the still-standing foundation thus produced (1903, p. 206).

Still another interpretation is given by Daly who, postulating the recent stability of the reef foundations here as well as in the Pacific, regards the flatness of the Maldive lagoon floors as testifying for the existence of platforms beneath them produced by the low-level abrasion of preexistent islands in the Glacial period. He gives several profiles illustrating the "topographic unconformity between reefs and platforms," the word "platforms" being confidently used here and in a number of other passages as if actual abraded surfaces and not simply aggraded lagoon floors were proved to exist by soundings. He adds, once again using "platform" as if it were synonymous with "lagoon floor": "No other banks better show the independent origin of reef and platform" (1915, p. 242). Were the Maldives situated in a marginal belt and in close association with cliffed residual islands, this view might find support in so far as its abrasional element is concerned. But it is unacceptable for reefs not far from the equator in a warm ocean, where the very existence of sub-lagoon platforms of abrasion is only an inference.

The views concerning the Maldives held by Agassiz, Gardiner, and Daly are, indeed, not supported by any independent and convincing evidence, and they therefore have no better standing than the earlier and also unverified view regarding the subsidence of the Maldive foundations announced by Darwin. Indeed, they have not today so good a standing, because Darwin's view of reef upgrowth on subsiding foundations is well and widely substantiated by the occurrence of unconformable elevated reefs in various parts of the oceans. On the contrary, Agassiz' view is wholly without independent verification. Gardiner's process of deep submarine erosion, reversed into the opposite process of submarine organic aggradation after the erosion is accomplished, has little to recommend it. Daly's scheme of the low-level abrasion of stable islands, invented particularly for the explanation of atolls, not only finds no support in any elevated reef structure yet described but is contradicted by the absence of plunging cliffs back of certain fringing reefs and close-set barriers, as well as by abundant evidence for insular instability.

Darwin on the Maldives

Darwin's views as to the formation of the Maldives were that "the bason-formed reefs . . . may, in fact, be briefly described as small atolls formed during subsidence over the separate portions of large and broken atolls, in the same manner as these latter were originally formed over the barrier reefs which encircled the islands of a large archipelago now wholly submerged." He thought it "not improbable that the first formation

of the Maldiva archipelago was due to a barrier reef of nearly the same dimensions with that of New Caledonia. . . . The barrier reef after repeated subsidence would become during its upward growth separated into distinct portions; and these portions would tend to assume an atoll-like structure" (1842, pp. 106, 110). This idea is elaborated below.

The gradual increase in the depth of the Maldive lagoons, from 20 or 25 fathoms in the north to 40 or 50 fathoms in the south, takes place over a distance of 400 miles. It would be difficult to explain this increase under the Glacial-control theory, even if the reefs had grown up from low-level abraded platforms as is there assumed; for some of the southern lagoon floors, although now shoaled by Postglacial aggradation from whatever depth their assumed rock platforms had when abraded, are still too deep to be accounted for by abrasion in an ocean that was lowered only 30 or 40 fathoms. Daly intimates, however, that the southward increase of depth may be due to "a more frequent killing" of the corals on the southern reefs in Postglacial time "by the stirring of the lagoon sediments" (1915, p. 215), thus holding to the postulate of stable reef foundations and of abraded platforms and, indeed, thus implying that the rock platforms beneath the shallower northern lagoons lie at as great a depth as that of those beneath the southern lagoons.

Darwin knew of the difference in depth of the northern and southern lagoons and wrote regarding it in the first edition of his book on coral reefs: "I can assign no adequate cause for this difference" (1842, p. 34). Yet it may be easily explained by assuming a southward increase of subsidence, as Darwin himself recognized in the second edition of his book, when he repeated the phrase just quoted and added: "Excepting that the southern part of the Archipelago has subsided to a greater degree or at a quicker rate than the northern part; and this conclusion agrees well with the fact that, in the Chagos group, lying 280 miles still farther southward, most of the atolls are sunken and half destroyed with the dead corals" (1874, p. 47). Nevertheless, independent proof of subsidence for the Maldives is still desirable before it should be asserted to have occurred, and such proof is hardly attainable in a group of atolls which include no high islands of decipherable geological history.

Evidence for Subsidence of the Maldive Foundations

In the absence of high islands near the Maldives appeal may be made to the neighboring part of the peninsula of India to discover whether it furnishes evidence for stability or instability of the ocean bed. According to Medlicott and Blanford (1879, p. 378), a larger land than that of peninsular India alone, presumably of moderate relief and altitude, was overspread with a heavy series of lava flows, the so-called Deccan traps, in Cretaceous time. The peninsular part of the lava-covered area, now raised to highland altitude, is limited on the west by a dissected slope known as the Western Ghats, where descent is made to the Konkan

lowland bordering the Arabian Sea. These experienced geologists stated that "the Western Ghâts rise from the Konkan in an almost unbroken wall, varying in height from 2000 to 4000 feet, cut back in places by streams, projecting here and there into long promontories, but preserving throughout a singular resemblance to sea cliffs"; they recognized, however, that other non-marine cliffs or escarpments resembled these "too closely in appearance to justify the assumption, without further evidence,

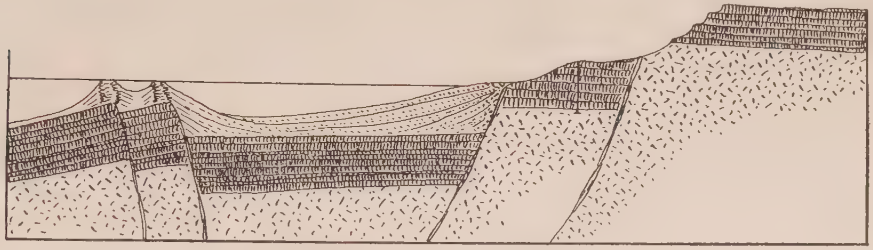


FIG. 226—Hypothetical section from the Maldive atolls to the southwest coast of India.

that the cliffs . . . are of marine origin" (1879, p. 378). But they did not specifically state that the cliffs had been originally a fault scarp or that the subsidence of the western part of the originally trap-covered land area and its disappearance in what is now the Arabian Sea was due to downfaulting. Yet in view of what has later been supposed as to the loss of a large continental area, known as Gondwanaland, between India and Africa and referred to in the citations from Gardiner's writings above, such downfaulting or downwarping of much of the Arabian Sea floor is very reasonably inferred.

Oldham later gave a fuller discussion to the origin of the trap escarpment in its relation to our problem. He conceived that at the beginning of the Cretaceous period the land of peninsular India "stretched away from the present west coast to South Africa" but that by the close of the Eocene period the "land connection between India and Africa had already been cut off, and that the gradual submergence of this continent took place during the last great period of earth-movements, leaving nothing to mark its original position but the coral archipelagoes of the Laccadive and Maldive Islands and the Great Chagos bank." He notes that the valleys by which the trap escarpment is dissected are "as a rule deep, narrow, and steep-sided" and the streams are "still actively engaged in deepening, and cutting back the heads of, their valleys." This appears to be due to "a recent elevation of the land which has not yet been counterbalanced by the cutting down of the valleys"; the recent elevation of Deccan plateau being the counterpart of the similarly recent downfaulting of the Arabian Sea floor. The largest rivers of the region head on the plateau within sight of the west coast and flow thence eastward across the whole breadth of the peninsula into the Bay of Bengal (1894, pp.

178, 179), thus suggesting that the upfaulting of the peninsula had given it an eastward slant.

The latest study of the Deccan trap escarpment in relation to a marginal fault is by Fermor, who reports upon the results obtained from a boring 1217 feet deep at a point 700 feet high, on the Konkan or coastal lowland. He concludes that the earth movements which "led to the foundering of the Deccan traps over what is now the Arabian Sea" affected also the coastal belt by leaving a block of small width at an intermediate level between the great depressed submarine area to the west and the great elevated plateau of the Deccan to the east (1922). Following this suggestion, Figure 226 represents my interpretation of the total faulted structure in relation to the Maldives and Laccadives. The figure is of course mostly hypothetical, but in view of all the reported facts it seems reasonable to take the foundations of those atolls to be slowly subsiding fault blocks, fragments of the lost Gondwanaland.

New Caledonia, Tagula, and the Maldives

The following interpretation of the Maldive atolls, based on Darwin's suggestion that they are derived from a barrier reef like the one which today surrounds New Caledonia, is offered in replacement of the interpretations quoted above from other authors. Like their interpretations, this one is at present unprovable; but it is believed to take fuller account of various pertinent facts than theirs do. It begins with the preliminary assumption that, during the submergence of Gondwanaland, most of the reefs which were from time to time formed here and there on the shifting shore lines of its subsiding slopes were, with shorter or longer delay, drowned at times of accelerated subsidence; for this reason, wide ocean spaces are reef-free today. Some warrant is found for this assumption in the explanation already given for the recent drowning of many longer-surviving reefs in the Nazareth Hermatopelago. The further exploration of the Indian Ocean may very likely discover inequalities in its floor that represent earlier- and deeper-drowned reefs of greater or smaller area.

The interpretation continues by assuming that the foundation of the Maldives was a double-crested mass, a pair of long, narrow, fault-block fragments of the lost Gondwanaland, as shown in Figure 226, each somewhat longer than New Caledonia, and that this mass either subsided somewhat more slowly than the rest of the vanished continent or perhaps experienced a local upheaval during the general subsidence elsewhere. Warrant for this assumption is found in the presumably slow subsidence of a similar continental fragment beneath the Nazareth Hermatopelago, still better in the survival into the present epoch, by reason of local upheaval, of the great island of Madagascar in spite of the deep subsidence of its surroundings.

It is eminently probable that fringing reefs may have been early established on the lower slopes of the double-crested, north-south mass

which was later changed by subsidence into a pair of sub-Maldive, fault-block islands, as they may be called, and that the early established fringes may have grown up for a time as a great single-loop barrier, *B′*, *B′*, Figure 227, over 400 miles long. But it is also probable that that great barrier was drowned at a time of rapid subsidence and replaced by fringing reefs of a new generation in the manner explained by Darwin (1842, p. 124), and that as subsidence continued these fringes in turn grew

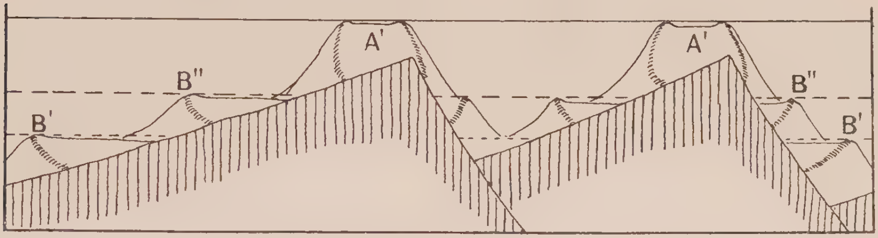


FIG. 227—Resolution of original Maldive barrier reefs into atolls.

up as two separate barriers, *B″*, *B″*, but of somewhat less length and breadth than their predecessor.

Whatever single barrier-reef loops may have been thus formed around the long sub-Maldive land mass during the earlier stages of its subsidence, the latest of them must have been eventually drowned and replaced by some 20 or 30 separate and much smaller barrier reefs, corresponding to the separate small islands into which the pair of large islands had by that time been resolved. It is these separate and small barriers that are supposed to have grown up, during further subsidence of their foundations, into the predecessors, *A′*, *A′*, of the present Maldive atolls. Speculative warrant for the foregoing explanation has already been given in the explanation proposed for the resolution of an originally continuous barrier-reef loop around the whole of the Louisiade Archipelago into about as many reduced barrier reef circuits as there are present-day reduced islands in the archipelago.

It must be next explained how it could happen that, in the latest stage of the island-chain subsidence and reef upgrowth, each predecessor atoll reef came to be subdivided into the circuits of minute atolls or faroes now existing there. Here speculative aid is again had from the Louisiade Archipelago, where the western part of the great Tagula barrier reef is broken up into many faro-like reef rings of small size, as has been briefly explained in Chapter XIII of this volume and in greater detail in one of my earlier articles (1922a). The explanation there proposed may be applied to the Maldive faroes as follows. The subsidence during which the predecessor atolls were built up was not long ago reversed into a moderate upheaval; warrant for such an upheaval being found in the still more recent upheaval of a number of reefs elsewhere in the Indian Ocean, as told in Chapter XVI. While upheaved, the predecessor reefs were

more or less dissected and thus resolved into rings of limestone islets. After the dissection was well advanced, subsidence was for a time resumed at such a rate and to such an amount as to drown any fringing reefs that had been formed on the emerged atoll flanks during the dissection of their crests; and then during a pause in this subsidence each limestone islet came to serve as the center of a new and minute fringing reef ring. Subsidence then continuing at a more moderate rate, each fringing reef ring grew up for a time as a minute barrier reef, until on the disappearance of the central limestone islet each minute barrier reef became a minute atoll or faro. Little reef patches in the Maldive lagoons may be explained as similarly built up from residual islets formed by the dissection of the emerged limestones in the lagoon floors of the predecessor atolls. The present Maldive lagoon floors would thus represent the lagoon floors of those predecessor atolls, more or less dissected and aggraded.

Glacial changes of ocean level, causing emergence and submergence and thus permitting the dissection of Preglacial predecessor reefs by low-level erosion and the upgrowth of new reef rings in Postglacial time, can hardly take the place of upheaval and renewed subsidence in the above scheme; for, if it did, circuits of faroes would be much more common in the Pacific than they actually are. The emergence of the Maldive atolls by upheaval may very likely have been earlier in date, greater in amount, and longer in duration than the emergence in the Glacial period.

It is hardly necessary to say that this long-drawn-out interpretation is hypothetical from beginning to end. Not a single one of its earlier elements is verified by the visible features of the Maldives, where the faroes and the banks they surmount are alone observable. But the interpretation has, nevertheless, the merit of taking into account the probable history of the sub-Maldive ocean floor, as inferred from the latest geological studies of the neighboring land border, and the further merit of being supported by what are believed to be present-day analogues at every step that it makes; and there the matter may rest.

Atolls in the West Indies

Mention has been made in preceding chapters of several elevated and submerged atolls in the West Indies; it remains to describe here a few examples of sea-level atolls in that region. Some of them occur in association with the slightly elevated atolls of the Bahamas and hence lie to the north of the Lesser Antilles, the reefs of which, as well as the islands of the Bahamas, have been described as belonging in the marginal belt of the Atlantic coral seas. Yet certain sea-level atolls in the Bahamas, as named below, appear to belong in the coral seas along with the sea-level barrier reefs of Cuba, which are not far away. Hence the division of the marginal belt from the coral seas proper is indefinite here.

One of the best atolls in the Bahamas is Hogsty reef, east of Cuba, HO

948, 4½ by 3 miles, the reef flat being from a quarter to a half mile in width and the lagoon from 3 to 5 fathoms in depth. Agassiz described this reef as a "regular horseshoe-shaped atoll" and wrote of it as follows at the beginning of his long continued experience in atoll exploration: "We passed three days studying the atoll. This to me was an entirely novel experience; we were at anchor [in the lagoon] in three fathoms of water, surrounded by a wall of heavy breakers pounding upon the narrow annular reef which sheltered us, forty-five miles from any land, with a depth of nine hundred fathoms only three miles outside our quiet harbor" (1894, p. 4). In a more general statement he wrote: "One cannot fail to be struck with the general resemblance of the Keeling atoll described by Darwin . . . to some of the smaller of the Bahamas Banks" (1894, p. 185).

A few other atoll-like structures are charted in the western part of the Caribbean Sea. They are Chinchorro bank, HO 966, 24 by 10 miles, with a narrow, fairly continuous reef and a shallow lagoon, not over 4 fathoms in depth. Farther south are Albuquerque and Courtown cays, HO 945, 5 miles and 6 by 3 miles, with less developed reefs. Alacran reef is a bank atoll on the Campeche bank north of Yucatan, HO 1240, 14 by 8 miles, in the southwestern part of the Gulf of Mexico; it has a continuous reef on the east, bordering a shallow reef flat from 2 to 4 miles wide, which gradually slants westward to a lagoon 6 or 8 fathoms deep. The reef on the west is less continuous and regular than on the east. Agassiz has pointed out that the action of the winds and waves has been important here in shaping the atoll (1888), as appears to be the case also in other bank atolls of the West Indies: but Alacran reef, much as it superficially resembles an atoll, can have little structural resemblance to the atolls of the Pacific coral seas, which rise from great oceanic depths. Los Roques, HO 2319, in an east-west range of high islands, 70 miles north of the Venezuela coast, is a somewhat imperfect atoll, 20 by 12 miles across. Many other banks with imperfect reefs occur in the Caribbean Sea.

Summary

It must be apparent from the foregoing pages that, much as may be learned regarding the present-day processes of reef formation from the study of atoll reefs, little has been learned from them as to the past conditions and processes of atoll formation. It is true that a number of experts who were engaged in the investigation of the origin of Funafuti Atoll by means of a deep boring in its reef became convinced that it had been formed by upgrowth during the subsidence of its unknown foundation, essentially according to Darwin's theory; but the constrained silence of those experts in their reports to the Royal Society, as far as theoretical matters were concerned, leaves that atoll in the position of a plaintiff whose well-qualified witnesses have not been allowed to testify regarding

the main question at issue. Hence less emphasis is here placed upon Funafuti, as an example of a Darwinian atoll, than upon the numerous atolls above named as situated in regions of independently demonstrated instability. But, as far as the origin of atolls in general is concerned, more emphasis still should be placed on the evidence for reef upgrowth during foundation subsidence that is provided by elevated barrier and atoll reefs, as presented in Chapters XV and XVI.

Indeed, the most significant piece of evidence provided by atolls themselves as to their origin is not derived from the large atolls, but from the minute atolls of the Pacific. For just as it is unreasonable to believe that the numerous large atolls can have been formed on slightly submerged, still-standing crater rims built up nearly to sea level, so it is unreasonable to believe that the numerous minute atolls and isolated reefs can have been formed on the summits of still-standing volcanic cones, built up nearly to or just above sea level. The only reasonable explanation for such reefs is that their small size is due to inslanting upgrowth on subsiding foundations, which originally rose to a very moderate height above sea level. Except in these few respects atolls taken by themselves are still good subjects for free speculation. It is for this reason that I have felt free to offer in the preceding sections a new interpretation for the Maldives; but in framing the interpretation I have been closely guided by the conclusions reached regarding the origin of better understood reefs.

CHAPTER XIX

REVIEW OF CONCLUSIONS DRAWN FROM THE PRECEDING CHAPTERS

The Disqualification of Various Incompetent Theories

So many facts have been presented in the second part of this book that it may be difficult for the reader to generalize their bearing on the theories analyzed in the first part. Yet certain results stand out clearly enough. The theory that shallow foundations have been prepared for reefs by the accumulation of pelagic deposits on still-standing deep banks, as Rein and Murray proposed; the theory that reefs have been chiefly formed on rising foundations, as set forth by Semper and Guppy; and the theory of reef outgrowth on stationary foundations, as proposed by Semper and Murray; likewise the theory of reefs based on platforms normally abraded on still-standing islands, as argued by Wharton and Guppy, or on platforms of erosion and denudation on still-standing islands, as urged by Agassiz, are all contradicted by a large body of pertinent evidence. The various processes assumed in these theories are incompetent to account for the persistently recurrent features of islands encircled by barrier and by almost-atoll reefs and for the unconformable contacts of elevated reefs with their subaerially eroded foundations. Even the examples of uplifted atoll and almost-atoll reefs—those of Roti and Barbados and perhaps of Christmas Island—that are based on pelagic deposits have been given their opportunity of growth not so much by the accumulation of those deposits in the manner suggested by Rein and Murray as by the upheaval of the previously subsided islands on which the deposits were laid down.

Nevertheless, the invention of these various theories has been an indirect benefit in the investigation of the coral reef problem, for their assumed conditions and processes have been thereby brought into consideration; and, on the theories being shown to be incompetent, the ground has been cleared for the examination of more competent theories. The benefit would, however, have been greater and more immediate if the inventors of the several theories had themselves deductively extended their postulated processes to the consequences that follow from them; but unfortunately this logical procedure was very generally neglected. Hence, instead of the field of investigation being cleared by the prompt removal of incompetent theories from it, it has for years been encumbered with their errors.

The Insufficience of the Glacial-Control Theory

The above-named theories being unacceptable, only two others remain to be examined; namely, Darwin's old theory of upgrowing reefs

on subsiding foundations and Daly's new theory of upgrowing reefs on platforms abraded on stationary foundations at a standard depth by the waves of the lowered Glacial ocean. In my judgment, the objections to the latter or Glacial-control theory analytically set forth in Chapter V are strongly supported by the array of facts systematically assembled in Chapters VII to XVIII. Low-level abrasion, the leading process of the Glacial-control theory, is truly found to have been operative on a number of islands in the marginal belts of the coral seas, where its work is proclaimed by plunging cliffs. But it has not been operative in the vastly larger area of the coral seas themselves, for there reef-encircled islands are prevailingly non-cliffed.

Let it be noted that, if no cliffed islands had been found in the marginal belts, it might perhaps be supposed that the prevailingly non-cliffed shores of the volcanic islands in the coral seas could be explained by the resistance that their lavas had opposed to low-level abrasion; but the strong lava cliffs of the marginal-belt islands disqualify this supposition. Moreover, the Glacial-control theory argues that the numerous coral-sea atolls have been built upon old, well worn-down, deeply weathered and completely truncated stable volcanic islands; but if so, a fair number of somewhat less old, subdued but not well worn-down, incompletely truncated and therefore strongly cliffed stable islands should also be found in the coral seas as foundations for barrier reefs; yet no such islands are found there. The only cliffed islands known in those seas are not subdued to moderate relief but are vigorously youthful or mature; and two of them, Tutuila and Tahiti, give indubitable signs of instability in the way of subsidence. The absence of subdued and well-cliffed islands in the coral seas militates strongly against a theory that entails their occurrence.

Furthermore, island stability, the fundamental assumption of the Glacial-control theory, is contradicted by several islands in the marginal belts and by many more in the coral seas. Indeed, all the reef-encircled islands of the coral seas which have a decipherable history are found to be unstable; and the instability of some of them must in all probability be shared by the foundations of a number of good-sized atolls that stand near them, especially in the Australasian region. Yet these atolls closely resemble many good-sized atolls of the open Pacific, from the visible forms of which no direct evidence of stability or of instability is to be secured. The close resemblance of these open-Pacific atolls to the Australasian atolls that stand near unstable barrier-reef islands makes the instability of practically all atoll foundations probable.

Furthermore, in view of the ordinary depth of lagoons in atolls that stand in regions of demonstrated instability, it is unwarranted to infer stability for vast areas of the ocean floor of unknown behavior, above which other atolls have similar lagoon depths. Hence, while it is perfectly true that many reef-enclosed lagoon floors and many submarine

banks in the coral seas have fairly accordant depths—this accordance of depth being the leading fact on which the Glacial-control theory is based—the explanation of that accordance by the low-level abrasion of stable reef foundations cannot be accepted. Explanation for it must be sought in the processes of some other theory.

Neglect of Deduction in the Coral Reef Problem

It must be here recalled, as Geikie pointed out when excusing his recantation of Darwin's theory (1883), that Darwin had studied only one good barrier reef, that of Tahiti, and had visited only one atoll, Keeling. It should not, therefore, occasion great surprise if Darwin's theory, grounded on so few facts of his own observation, had been found erroneous when it came to be confronted with a larger variety of facts observed by others. And erroneous indeed it was thought to be by a number of later observers, who were driven by their wider experience to give it up, in spite of their previous belief in it. But unluckily for them, their abandonment of the older theory was quite as serious a misjudgment as their adoption of newer alternative theories of their own invention. For in their observations they and their contemporaries overlooked structures as simple and as significant as unconformable contacts, and forms as manifest and meaningful as shore-line embayments; and in their discussion they and their followers neglected the logically essential process of deduction to a fatal degree.

The neglect of the deductive side of this theoretical problem seems to have prevailed through so late a period in the evolution of scientific method as the last twenty years of the nineteenth century, when the origin of coral reefs was more actively discussed, chiefly in England, than ever before or since. Several leaders in geological science of that time were drawn into the discussion, especially when the Duke of Argyll implied, as has been told in Chapter IV, that new views concerning the origin of coral reefs were suppressed by a conspiracy of silence. Yet even then the importance of the deductive side of the problem was little emphasized, and the deductions that ought to have been made were very imperfectly carried out. It was as if the quiet and reflective process of deduction had attained no recognized place alongside of the active outdoor duty of observation in scientific investigation. Hence it was natural enough that Darwin also, at a somewhat earlier period, was almost as little attentive to deduction as were his successors. His theory now survives not because he, who later became so deservedly famous, invented it; not because his discussion of it was complete; but because he had the good fortune to hit upon a simple process of reef development, which has been found to work satisfactorily when it is tested by the impartial confrontation of its many consequences, more thoroughly deduced than ever he deduced them, with a large accumulation of facts, more critically observed than the voyagers of his time ever observed them.

The Competence of Darwin's Theory

The simplicity of Darwin's theory of island subsidence and reef upgrowth is as striking as its success. When its various deduced consequences are confronted with the appropriate facts, the agreements found are truly marvelous. It is of great significance that many essential consequences of the theory, altogether unsuspected by its young inventor, correspond most convincingly with facts of widespread occurrence of which the inventor of the theory had no knowledge whatever. The theory therefore meets the critical requirement of explaining not only the facts that it was invented to explain—namely the sequence of reef forms from fringes through barriers to atolls—but also many other facts of an altogether different nature concerning reef-encircled islands, some of which had not even been discovered when the theory was announced. Its capacity to accommodate these later-found facts is most commendable; for, by doing so, it shows extraordinary competence where its rivals show utter incompetence.

In support of this deliberate conclusion it is hardly necessary here again to mention the occurrence of embayed shore lines back of upgrowing barrier reefs as a necessary consequence of Darwin's theory and to recall the universal presence of such shore lines in association with the reefs that front them; or the occurrence of low, non-cliffed, mountain-top islets as a necessary consequence of the theory in almost-atoll lagoons and the presence of precisely such islets in the lagoons of several almost-atolls, as far as their islets are described. But it is important to note that the rock bottoms in the embayments of many reef-encircled volcanic islands are believed to be of much greater depth and width than can be accounted for by the low-level erosion of still-standing islands during the Glacial epochs, and also to note that the embayments of the southwestern coast of New Caledonia and of the northeastern coast of Australia, back of the two greatest barrier reefs of the world, occupy the distal parts of valleys in maturely dissected land slopes, the open erosion of which must have demanded a longer time than can have been provided by all the Glacial epochs together. The lowering of the Glacial ocean during those epochs may have permitted the renewal of erosion on such parts of the maturely excavated valleys as had been previously submerged by subsidence and as were then temporarily emerged; but the now embayed parts of the valleys could not have been excavated to their present form by such short-lived erosion alone: hence the coasts must have subsided as Darwin supposed.

Similarly, it is hardly necessary once more to explain that unconformable contacts of reef and lagoon limestones with their foundations are as essential consequences of Darwin's theory as embayed shore lines are, or yet again to state that such contacts have been found wherever elevated and dissected reefs have been adequately studied. But the

high significance of the best known contacts between barrier-reef and atoll limestones and their foundations—those of Mangaia, Eua, Tuvuthá, and the Exploring Isles—as impartially exposed samples of many others deserves to be again pointed out. And with those well certified examples of barrier-reef and atoll contacts, which serve so well as expert witnesses for Darwin's theory, should be associated the many more well certified examples of unconformable contacts of elevated fringing reefs with their foundations in the Australasian archipelago, the proper understanding of which corrects their misinterpretation as contradicting Darwin's theory and gives instead, as illustrated in Figure 19, unqualified confirmation for certain of its phases.

And let it be explicitly emphasized that, as stated at the beginning of Chapter XIII, while a depth limit of about 20 fathoms for coral growth is an inherent postulate of Darwin's theory as he made it and left it, the evidence, based on drowned valley embayments and unconformable reef contacts, for the small depth at which various barrier and atoll reefs began their growth is entirely independent of that postulate and therefore gives independent support for it.

On the other hand, it is desirable to bring forward with renewed emphasis certain less familiar matters, which, even though they are still somewhat speculative, have a peculiar value as confirmations of Darwin's theory because of the unexpected manner in which they fit into it. One of these is the probable delay in the establishment of coral reefs on young volcanic islands until after the valley mouths of the islands are embayed, as explained in Chapter VI. For it thus appears that early-formed reefs depend upon subsidence for their opportunity to befringe an island about as much as barrier reefs do for their opportunity to grow up and encircle one. Another altogether unexpected matter is the aid given by subsidence in the disposal of the great volume of detritus that must be discharged from the valleys of a young volcanic island while its dissection is in active progress, and also in the submergence of the cliffs that must have been cut around the island during at least the earlier stages of that discharge before the island shores were defended from wave attack by persistent upgrowing reefs. Thus not only the disposal of the detritus but also the establishment and survival of fringing reefs seem to depend upon Darwin's principle of subsidence as much as does their eventual upgrowth into barrier reefs. Darwin builded better than he knew.

Subsidence as an Aid in Correlating Unlike Islands

Aberrant islands like reefless Réunion, still in an early, undefended, and therefore cliffed stage, are brought by subsidence into systematic relation with older islands that have reached an embayed and reef-encircled stage. Moreover, the general absence of plunging spur-end

cliffs on the embayed, reef-encircled islands of the coral seas today demands that the cliffs which were presumably cut around them in their reefless youth have now disappeared; and this again is best explained by island subsidence. That the cliffs of Tahiti have not yet sunk enough to vanish, except at the presumably least cliffed, northwestern curve of the island, and that the cliffs of near-by Mŏorea have all vanished, except those where abrasion was presumably longest continued, only serves to show how well "Exception proves the rule." Clearly, the cliffs of these exceptional islands cannot have been cut by low-level abrasion while the islands were temporarily undefended by reefs in the Glacial epochs; for in that case all the other barrier-reef islands of the coral seas ought to be similarly cliffed; and they are not.

Darwin's theory is thus seen to be successful not only in bringing the prevailing features of islands and reefs into systematic correlation but also in providing means of giving reasonable explanation for special and peculiar islands such as Réunion, Tutuila, Tahiti, and Moorea. A few other islands and reefs which test the value of the theory in this delicate way may be instanced. For example, the excentric position of Clipperton Rock, which rises from a reef ring instead of from near the center of the ring, would be difficult to explain under any other theory; but under Darwin's it is a perfectly natural consequence of the subsidence of a peak with unsymmetrical slopes while an in-slanting reef grows up around it. Again, the occurrence of Misima with its terraces of unconformable uplifted reefs in close association with Tagula and its great sea-level barrier reef is beyond explanation by any of the still-standing theories, unless departures from their main postulates are introduced; but it is perfectly expectable under Darwin's theory, in which the possible upheaval of one area while a neighboring area is subsiding is explicitly recognized. Another and even more striking instance of the ease with which Darwin's subsidence theory explains certain matters difficult of explanation under other theories is found in the numerous minute reefs dotting the coral seas, as noted in Chapter XVIII. For under all the still-stand theories these reefs must be based on submarine mountains, presumably volcanic cones, the summits of which just reached or just failed to reach sea level not long ago; and that so many peaks should recently rise to so nearly a uniform altitude is unimaginable. But under Darwin's theory the occurrence of small reefs is the inevitable result of the gradual subsidence of supermarine volcanic summits that were originally built up at various dates to any ordinary size and height above sea level. Still another special feature of reef development yet to be mentioned may perhaps be regarded as not well enough established to be cited here in proof of the competence of Darwin's theory to meet peculiar conditions. It is the resolution of a single, extensive, early-formed reef loop into a number of separate smaller reefs in consequence of the slower and faster subsidences of its mountainous foundation. Yet such a resolution of

one large into many smaller reefs has pretty surely taken place in the Louisiade Archipelago; it seems recently to have occurred, after long delay, in the Seychelles; I believe it has happened twice in the Maldives; and it is a highly probable future possibility for New Caledonia.

Evidence Given by Nullipores for Darwin's Theory

The presence of nullipores in coral reefs was fully recognized by Darwin; their importance as reef binders has been emphasized by later students. Indeed, some biologists, assuming that nullipores can live at depths of 1000 fathoms or more, have suggested that such nullipores might build up barrier and atoll reefs from great depths on stationary foundations, thus leaving only a surface rim, some 20 fathoms thick, to be added by corals. But, if this were so, the nullipores must have lived in water of low temperature; and if they can live in low-temperature water they might build up reefs without the aid of corals from considerable depths in the cooler seas. Yet no such nullipore reefs are found in the cooler seas. On the other hand, inasmuch as deep-founded barrier and atoll reefs have the same geographical limits, evidently determined by surface water temperatures, as fringing reefs, it would seem that the distribution of deep barrier and atoll reefs must have been determined by the same temperature control as that which limits shallow fringing reefs and, therefore, that deep barrier and atoll reefs must have begun as shallow fringing reefs, as Darwin's theory assumes.

It may be added that, whatever the importance of nullipores may be as reef binders, they do not seem to have been able to play the rôle of reef makers in the marginal belts of the coral seas when the surface waters were chilled—but not to the low temperatures now prevailing at depths of 1000 fathoms or in high latitudes—during the Glacial epochs.

Freedom of Darwin's Theory from Special Pleading

A meritorious feature of Darwin's theory is its freedom from what may be called special pleading. It does not arbitrarily exclude reef growth in order to permit abrasion and then as arbitrarily introduce reef growth after abrasion has ceased, as Wharton's and Guppy's platform theories do. It does not impose any special condition, such as long enduring stability, upon the islands of the coral seas but takes them as it finds them. Coral reefs have to run their chances, whether islands are rising, still-standing, or sinking; or first rising and then sinking; or first sinking and then rising. If an island stands still for a time, a reef will grow outward and gain unusual breadth while its lagoon is aggraded; witness the three-mile reef flat and the shallow lagoon of Christmas Atoll. If an island sinks too fast for an upgrowing reef to maintain its crest at sea level, the island will be merely terraced with thin fringing

reefs whenever pauses in the sinking take place; witness many examples in the East Indies. If an island sinks not too fast, a fringing reef will grow up and form first a barrier and later an atoll; and either barrier or atoll reef may be afterwards uplifted; witness Mangaia and Eua, Tuvuthá and the Exploring Isles. If an island subsides slowly at first and then faster, a fringing reef of second generation will succeed a barrier reef of first generation; witness Palawan. If rapid sinking follows the attainment of the atoll stage, the atoll will be drowned; witness Chagos and Macclesfield and a host of others; and so on, almost indefinitely.

The Comprehensiveness of Darwin's Views

Another merit of Darwin's views is their many-sided comprehensiveness. He is thought by some, who have not read his book carefully enough, to have explained only the transformation of fringing reefs into barriers and barrier reefs into atolls by reef upgrowth during the slow subsidence of the reef foundations; but, as has been shown in Chapter II, his consideration of coral reef origins was much broader than that. His subsidence theory naturally gained prominence over his other views because of its widespread application to the many atolls of the Pacific as well as because of its attractive simplicity. But he proposed also a highly competent explanation for many fringing reefs following rapid subsidence instead of following upheaval; and a perfectly possible explanation for atolls without the preliminary production of barrier reefs. He did not even reject the crater-rim theory of atolls altogether but was satisfied with "knocking it on the head," as Lyell said; that is, with pointing out the extreme improbability of its general application.

The Elasticity of the Subsidence Theory

Still another merit of Darwin's theory is its elasticity, as compared with the rigidity of all the still-stand theories. It is for this reason that the vigorous old theory is not in the least embarrassed by the occurrence of many kinds of reefs in close association in eastern Fiji, in spite of the misunderstandings to which such an association has given rise in the minds of some of Darwin's critics. For when the reefs of that most interesting region are deliberately examined, their apparent complication may be simply and systematically explained as due to a few changes of level caused by the westward passage of a broad and low anticline and its accompanying synclines. The concept of such an anticline is, of course, wholly outside of Darwin's theory, but such is the adaptability of the theory that it rides over the anticline as easily as a well-rigged ship rides over a heavy sea. Reefs that were built up while their foundations were sinking with the approach of the preceding syncline were upheaved and eroded on the lift of the anticlinal front, but they are

submerged again for the upbuilding of new reefs as the rear of the anticline lowers them into the following syncline.

It is a strong point in favor of a theory if it can correlate the various forms of islands and sea-level reefs that are found in the Society group, as described in Chapter XIII. It is even a stronger point in its favor if it can, as just pointed out, so easily enter into combination with the peculiar manifestation of diastrophism found in eastern Fiji where sea-level and elevated reefs occur and thereby can bring orderly arrangement out of seeming confusion, as explained in Chapter XVI. A highly exceptional feature there discovered, the adequate explanation of which is immediately provided by this happy combination, deserves to be recalled here; it is the eastward slant of the Exploring Isles lagoon floor, the like of which is not often found elsewhere in the wide stretch of the coral seas. The slant seems at first to be merely an aberrant and independent item of fact, unrelated to the many other and greatly diversified items of fact that abound in its region. But when better understood, the exceptional slant is seen to be only one of the many necessary consequences of the changes of level caused by the westward migrating anticline, on the rear slope of which the Exploring Isles now find themselves.

He must be a convinced advocate of some other theory who can discredit witnesses so competent and so consistent as those which here testify for Darwin's theory; for so the Exploring Isles do testify most impartially. Their limestones, resting unconformably on an eroded volcanic foundation, record a time of deposition while the Isles were subsiding in the preceding syncline. The erosion of the limestones, by which their foundation was revealed, took place when the Isles were rising with the approach of the anticlinal crest. The upgrowth of the present fine barrier reef has accompanied the sinking of the Isles in the following syncline. And yet these Isles are only the most outspoken of a cloud of other witnesses, all of which, marshaled in orderly array in the several north-south belts of eastern Fiji, have so long waited to be summoned before the court of scientific inquiry. One of the nearest approaches to a repetition of the slanting floor of the Exploring Isles lagoon is found in the Tonga Banks, the slant of which probably has an explanation similar to that above noted: perhaps the slanting floor of the Panniet lagoon in the Louisiade Archipelago also deserves mention in this connection.

The Adaptability of Darwin's Theory

But is the old theory really so universally competent that it finds no difficulty in explaining all the facts pertaining to coral reefs? Yes, very nearly so; for, if broadly considered, it certainly meets and explains many facts that have been thought to argue against it. For example, the prevalence of embayments in the continental coasts of the world has been taken to mean that the ocean surface has recently risen; and

such a rise has been held to be inconsistent with the broad oceanic subsidence that Darwin's theory has been erroneously thought to demand in the atoll regions of the Pacific. Yet if the concept of a broad subsidence of the ocean floor, which Darwin himself extended from his theory of reef formation, is replaced by Molengraaff's concept of the relatively local and isostatic subsidence of volcanic islands—a concept that is entirely compatible with Darwin's theory of coral reefs—this inconsistency largely disappears. For the upbuilding of many huge volcanic cones on the floor of the Pacific must have caused a considerable rise of ocean level; and the later partial subsidence of the cones would cause but little lowering of the ocean, because as the cones subsided their crests became crowned with great reef terraces; and be it remembered here that the withdrawal of reef-making limestone from solution in the ocean water does not diminish the volume of the ocean by the volume of the withdrawn limestone. Hence, thus interpreted, Darwin's theory of upgrowing reefs on subsiding foundations need not involve a general lowering of the ocean surface.

The great thickness demanded by the old theory for barrier and atoll reefs has also been held to be an objection to it in view of the small thickness found in many uplifted fringing reefs, but this objection has little weight. For, in the first place, the small thickness of uplifted fringing reefs has been shown in Chapter II to be chiefly due to the rapid subsidence of the islands on which they were formed; and the great thickness inferred for barrier reefs has been shown in the same and in later chapters to be altogether reasonable, in view of what is known of island forms and of island movements. It may be here recalled that the measurable thickness of the barrier reef that surrounds the Exploring Isles in eastern Fiji is nearly 500 feet over the lagoon floor in the eastern part of the reef circuit; that the fairly inferred thickness of the barrier reef of Wakaya in central Fiji is at least 1000 feet; and that 2000 feet is not an unreasonable thickness for the barrier reef of Borabora in the Society group, in view of the great subsidence apparently suffered by that island.

It must not be forgotten that the slowness of island subsidence postulated by Darwin is no real objection to his theory; for, wherever reefs maintain themselves at sea level, whatever subsidence their foundations have suffered cannot have been faster than the rate of reef upgrowth. On the other hand, Darwin's theory sets no limit on the rate of island subsidence; it merely postulates that, where subsidence is not too rapid, reef upgrowth may counterbalance it. The average rate of subsidence in the atoll regions of the Pacific can therefore have been no faster than the average rate of reef upgrowth. Such subsidence has been much slower than the ordinary rate of island displacement in the East Indies and also much slower than the inferred rate of changes of ocean level during the Glacial period.

An Important Modification of Darwin's Theory

Yet in one important respect, the old theory does prove wholly incompetent. It cannot explain the peculiar features of marginal-belt islands and reefs without borrowing from its newest competitor the important factor of low-level abrasion, as has been shown in Chapter VIII. However, even when modified by the addition of this factor, subsidence remains dominant in the modified theory. On the other hand, its newest competitor, the Glacial-control theory, is I believe irretrievably crippled by the limitation of its chief process—low-level abrasion—to the marginal belts, to say nothing of the general invalidation of its chief postulate, island stability.

The Accordant Depths of Lagoon Floors

Those who have adopted the Glacial-control theory may, however, feel that the chief fact upon which it is based—namely the fairly accordant depths of many lagoon floors and submarine banks in the coral seas—still remains beyond explanation by the subsidence theory. I must agree with them to the extent of recognizing that this is the one fact which the subsidence theory does not explain easily. Nevertheless, I believe that the accordance of many lagoon depths, along with the not infrequent discordance of other lagoon depths, must eventually be accounted for by the old theory in its modified form, for the following reasons. In the first place, the success of the theory of subsidence in so many other respects makes it very probable that it must be successful in this respect also. In the second place, wherever subsidence has been so slow that upgrowing reefs have kept their crests at sea level, lagoon floors may well have been accordantly aggraded. Indeed some of them are today supplied with so much sediment that part of it is exported by outflowing currents; and such exportation is likely to be especially active in checking the aggradation of lagoon floors when they become unduly shallow. In the third place, several additional agencies for the equalization of lagoon depths have been pointed out, among which the low-level degradation of shallow lagoons during the lowered stands of the Glacial ocean may be here recalled. In the fourth place, the known variations of lagoon depth are too great to be explained by the Glacial-control theory. In the fifth place, it may be here once more stated that the occurrence of barrier reefs and atolls with lagoons of ordinary depth in regions of established instability demonstrates that such ordinary depths may be given in unstable regions, while it opposes the acceptance of atolls with similar lagoon depths in the mid-Pacific as proving the long-enduring stability of that vast region. The lagoon depths there found must be explained by Darwin's theory of subsidence, modified by the addition of Glacial changes of ocean level, as above noted.

A Modification of the Glacial-Control Theory

In view of the improving modification of Darwin's theory by this addition, as noted in Chapter V, a restriction, a rejection, and a suggestion regarding the Glacial-control theory, already made in that chapter, may be repeated. The restriction is the limitation of low-level abrasion to the marginal belts of the coral seas. The rejection is that the long-enduring stability of reef foundations demanded by the Glacial-control theory cannot be equated, as has been proposed by its author, with one of the pauses which Darwin noted as probably interrupting the long continued subsidence of certain islands, according to his theory. The suggestion is that the slow subsidence postulated in Darwin's theory—the occurrence of subsidence being proved by various independent lines of evidence, and the slowness of subsidence being proved by the capacity of many reefs to maintain their crests at sea level in spite of it—should be taken as the equivalent of a long quasi-stability, which may perhaps satisfy a revised form of the Glacial-control theory. The improving modification of Darwin's theory by the addition of low-level abrasion in the marginal belts would then be balanced by an improving modification of the Glacial-control theory by the relaxation of its postulate of long-enduring stability into a postulate of extremely slow subsidence. But if the Glacial-control theory, already stripped of the leading factor of low-level abrasion in the coral seas, adopts this suggestion, it will simply merge into Darwin's modified theory, which will then hold the field alone; and so I believe it will right worthily, when it is given full and critical consideration.

Postscript

After forming an early acquaintance with Darwin's theory of coral reefs sixty years ago when I was a student in one of Shaler's classes in geology at Harvard University, those strange oceanic structures were relegated to the dim background of my thoughts; and there they remained ten years later when, on returning to Harvard as a teacher of geology at first and of physiography afterward, my attention was increasingly directed to the study and description of the forms of the lands. Not until that study had been continued some twenty years did I come accidentally upon the inference, while drawing an ideal block-diagram of a barrier reef for an elementary textbook, that if such reefs are formed by upgrowth around subsiding islands, as Darwin's theory proposed, the islands should have embayed shore lines. Then, on discovering from the charts of such islands that they do have embayed shore lines, the theory of subsidence seemed to me to be a true theory.

But it was at about that time that Agassiz' report on the reefs of

Fiji appeared; and his conclusions, reached after he had seen many well embayed islands, were so strongly opposed to Darwin's theory that my confidence in it was shaken; all the more so because of favorable references to several competitive coral reef theories invented twenty or thirty years before that time by Semper, Rein, Murray, and Guppy, which I had met in reading and in none of which embayed shore lines were given any consideration. It was not until several years later that, on looking up Dana's report on the Geology of the Wilkes Expedition, I learned much to my surprise that he had clearly made application of the principle of shore-line embayments to the coral reef problem a long half-century before and had thus provided for Darwin's theory a support greatly needed by it. Yet on reading more recent authors I found to my still greater surprise that Dana's confirmation of Darwin's theory had been overlooked and neglected by nearly every one of them. I therefore called attention to this neglect in a special article on the centenary of Dana's birth (1913).

My interest in the old problem was thus aroused, and all the more strongly on perceiving that the studies of land forms to which I had been chiefly devoted might find novel application on reef-encircled oceanic islands. Hence, when, two years after resigning my professorship at Harvard in 1912, opportunity came to cross the Pacific, I made preparation therefor by reviewing all the coral reef theories then current (1914) and then set out on a long voyage, the route of which as outlined in an earlier chapter enabled me to see thirty-five reef-encircled islands and a long stretch of the Queensland coast back of the Great Barrier Reef of Australia—a glorious observational opportunity. It was, as already told at the beginning of this volume, my intention on returning home to prepare at once an account of that voyage; but as my manuscript advanced it became more and more apparent that the coral reef problem as a whole was in need of a comprehensive and critical review; thus the plan of the present volume was gradually developed.

Work upon it has brought me many enjoyable experiences, among which are to be counted the recognition of a delay in the establishment of fringing reefs on a young volcanic island until after both its dissection and its subsidence are somewhat well advanced; also the interpretation of the evidence for continued subsidence as furnished by the disappearance of large volumes of island detritus; to say nothing of the detection of the likeness and the contrast between the formerly cliffed and now reefless Madras coast of India and the formerly cliffed and now reef-fronted northeastern coast of New Caledonia or of the evidence given by the small thickness of many uplifted fringing reefs for instead against a certain phase of Darwin's theory. Greater enjoyment still came from the discovery, prompted by the climatic factor of the Glacial-control theory, of the marginal belts of the coral seas, for that seems to me a long step forward in the home study of coral reefs; and also from the

confirmation of the occurrence of a marginal belt in the Atlantic as secured from a visit to the Lesser Antilles in 1923. The same may be said of the illuminating contrast between the island-free and therefore never reef-protected southern half of the coast of eastern Australia and the island-swarming and therefore long reef-protected northern half; for in this contrast seems to lie a complete refutation of the idea that the Great Barrier Reef is of recent formation on a northward prolongation of the southern continental shelf of that far continent. The latest items of these many enjoyments came during the final revision of the preceding chapter: they are the evidence given by minute oceanic reefs for the subsidence of their foundations and therefore for the subsidence of the foundations of larger atolls also, and the evidence given by nullipores for the shallow origin of barrier and atoll reefs. But the most gratifying experience during the progress of this investigation has been that of seeing many complicated facts of apparently disorderly occurrence—those of eastern Fiji, for example—arrange themselves in orderly sequence as soon as their explanation came to be guided by the clue of Darwin's theory.

Through all this period of observation and study I have therefore felt a growing admiration for the keen insight of the young naturalist of the *Beagle* and have thus come to appreciate better than ever before the calm fairmindedness with which he, in his maturer years, taught a new philosophy to an unwilling world. It has been a great pleasure to try to secure for his early-framed theory of coral reefs, which after worldwide adoption between 1840 and 1870 was so strongly objected to and even rejected by a number of later observers between 1870 and 1910, the broader consideration that it so fully deserves. The theory was only an outline in the form conceived by Darwin; for the facts of the coral reef problem were then imperfectly known, and various phases of the theory itself were left undefined. Yet, as new facts have been brought to light, it has been most impressive to note the ease with which they have been explained by inevitable extensions of the old theory. The explanations were, indeed, latent in the theory from the beginning. The only serious exception to this statement concerns the islands of the marginal belts of the coral seas, for the explanation of which Darwin's theory must be supplemented by the wholly new process of low-level abrasion, first brought into the problem in recent years by Daly. Thus modified, the success of the old theory in explaining many more facts than those which it was invented to explain gives assurance of its being a true mental counterpart of the invisible conditions and processes of the past under which the coral reefs of today have been developed.

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